# APPENDIX A

# Why Magnetized Target Fusion Offers A Low-Cost Development Path for Fusion Energy

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# I. Introduction

Reasonably priced energy supplies have become an expectation of the developed world and a necessary ingredient for development of Third World countries. The problem of providing large supplies of low-cost energy is a long-term, complex one that requires sustained R&D efforts, in spite of the shadow cast on long-term R&D by the federal deficit problem. The role of fusion energy as a power source was thoroughly reviewed and strongly endorsed in 1995 by the President's Committee of Advisors on Science and Technology Fusion Review Panel chaired by John Holdren. He argued [Holdren 95]:

> *The options available for meeting the world's demand for energy in 2050 and beyond are those already in use – fossil fuels, biomass energy, nuclear fission, hydropower, geothermal energy, wind energy, and solar energy – plus, potentially, nuclear fusion.*
>
> *In these circumstances, it should be obvious that there is great merit in the pursuit of diversity in energy options for the next century. There are not so many possibilities altogether. The greater the number of these that can be brought to the point of commercialization, the greater will be the chance that overall energy needs can be met without encountering excessive costs from or unmanageable burdens upon any one source.*

In the past decade the critical issue for fusion has shifted from one of scientific feasibility to one of commercial viability. The specific problem is that all fusion technologies currently being pursued involve extremely costly facilities for the required steps of further development. In the present international fiscal environment, it is imperative to find a more cost effective development path for fusion energy.

The conventional regime of Magnetic Fusion Energy (MFE), with plasma density $n \sim 10^{14}$ cm$^{-3}$ and magnetic field provided by superconducting magnets, has been relatively well explored [Sheffield 96]. Tokamaks are the major devices studied in MFE, and tokamak research has tremendously advanced our understanding of plasma physics. The International Tokamak Experimental Reactor (ITER) design illustrates the technology and cost for an ignited plasma demonstration in the MFE regime. The estimated $10-billion price for ITER calls into question whether fusion can ever be developed based on tokamak-like technology. Factors of a few, or maybe ten at most, in any parameter such as size, neutron wall loading, and so forth are about all that one can credibly seek in optimizing a tokamak system. Certainly research seeking to reduce the ITER-like system size by factors of a few is extremely important and needs to be pursued. But we strongly suspect that the necessary breakthrough, which would allow fusion to be developed in a more timely and affordable manner, will involve a qualitatively different and significant departure from the MFE tokamak regime and technology.

Another approach to fusion, Inertial Confinement Fusion (ICF), represents a good alternative to MFE in that the regime of density and pressure is completely different, the physics issues are quite distinct, and the technology required has fairly little in common with a tokamak-like system [Lindl 95]. Thus, the issues that are likely to emerge as limitations for one approach are unlikely to apply to the other. Unfortunately, the cost of developing ICF is also high. The price of the National Ignition Facility (NIF), which will demonstrate ICF ignition, is over $1 billion.

The anticipated cost of developing efficient inertial fusion drivers such as heavy ion beams is also high [Bangerter 97]. For the development of fusion energy, something less expensive would obviously be desirable.

**A Lower Cost Alternative—Magnetized Target Fusion**

To find a lower cost approach, we start by noting that the cost of development is directly linked to the system size, which in the case of MFE is mostly dictated by the maximum magnetic field strength obtainable with superconducting magnets. The critical constraint with ICF is the costly high-power drivers needed to achieve the extreme conditions of density and pressure.

We also note that countless examples can be found in the magnetic fusion literature showing that fusion reactions can be created in smaller-sized systems if one admits larger magnetic field, higher plasma density, and pulsed operation as with imploding liners [Sherwood 81, Lindemuth 83, Robson 76, Vekshtein 90, Ryutov 96, Gross 76]. In this paper we will review the basic reason for that tendency, and examine some of the consequences. We will conclude that the most interesting regime of density is n ~$10^{20}$ $cm^{-3}$, which is high compared with MFE, but low compared with ICF. This density regime at 10 keV temperature corresponds to megabars of pressure (millions of atmospheres), which is intrinsically pulsed in nature.

We define the intermediate density regime to be Magnetized Target Fusion (MTF). The name is chosen based on two general characteristics that we assume for MTF: 1) as with ICF, PdV work heats the fuel by compressing it inside an imploding wall, or "pusher" in the parlance of ICF, and 2) magnetic field is embedded in the fuel to insulate it from the pusher.

Although numerous variations in approach can be envisioned, we have in mind the magnetically-driven imploding liner method for MTF. In the liner approach:

- fuel with an embedded magnetic field would be preheated and positioned inside a volume of centimeter dimensions, which is surrounded by a thin metal shell (or liner) that will act as the pusher,
- a current introduced on the outer surface of the liner would cause it to implode by self-pinching magnetic forces at a velocity of approximately $10^6$ cm/sec,
- the liner would be made thick enough that the pinching current does not vaporize it, and therefore the liner would be a flux-conserving metal shell during the implosion,
- at peak compression a significant fraction of the liner kinetic energy would be converted to thermal energy of the fuel, and
- the dwell time of the liner at peak compression and the final fuel density and temperature would be designed to give significant fusion energy generation.

The liner velocity required is termed hypervelocity because the kinetic energy density exceeds the heat of vaporization for liner materials. The technology for precision implosions creating millions of atmospheres of pressure is a challenge in its own right. In the 1970s when a number of MTF-related efforts were underway, most of the effort was directed towards developing this demanding technology, and very few integrated tests with a preheated plasma were ever done. In what must be viewed as a serendipitous coincidence, the Department of Energy's Office of Defense Programs (DP) in the last decade has significantly advanced the technology of imploding liners with the same parameters of implosion velocity and kinetic energy as those needed for investigating fusion reactions in the MTF regime. The purpose of the Defense

Program work is to study and understand hydrodynamics in the megabar pressure regime and has no connection with nuclear fusion. However, the existence of DP expertise and facilities offers an important near term advantage for resuming MTF research.

The magnetic field to insulate fuel from its surroundings is the essential ingredient of MTF. In fact, the benefit of a magnetic field in a fusion target was recognized in the 40's by Fermi at Los Alamos and at approximately the same time by Sakharov in the former Soviet Union. We will derive below the advantages in terms of reduced energy and power that must be delivered to the fusion fuel. The advantages of MTF can also be expressed in terms of requirements on driver technology. By preheating MTF fuel to between 100 and 500 eV, the volume compression needed to reach 10 keV temperature is 100-1000. The volume compression ratios for ICF are typically 30,000 to 60,000, which requires a much more precise implosion system. The characteristic implosion velocity for MTF is 0.3-3.0 cm per microsecond, which is 10 to 100 times smaller than for ICF. The peak pressure for MTF is 1-10 megabars, and for ICF, 100s of gigabars. These impressive differences justify careful examination of ways to introduce a magnetic field.

## II. The Technical Case for Magnetized Target Fusion

### A. Lawson Condition for Pulse Duration and Energy Confinement Time

In a pulsed system, as opposed to steady-state, the pulse duration, $\tau_{burn}$, is an important new variable. The pulse duration determines the amount of fuel that reacts or "burns," given the reaction cross section, leading to an $n\tau_{burn}$ requirement in a similar way that $n\tau_E$ is determined from power balance in a steady-state system. For deuterium (DT) fuel the thermonuclear reaction rate per unit volume is

$$R = n_D n_T <\sigma_{DT}\, v> = 1/4\, n^2 <\sigma_{DT}\, v> \qquad (1)$$

where $n_D$=$n_T$ is the deuterium and tritium density, n =$n_D$+$n_T$ is the total ion or electron density, and $<\sigma_{DT}\, v>$ is the averaged product of cross section and relative velocity for a Maxwellian velocity distribution. At 10 keV, $<\sigma_{DT}\, v> \cong 10^{-16}$ $cm^3$/sec. The total density decreases at the rate 2R as the fuel is consumed, and the frequency of fusion reactions per ion for either deuterium or tritium ions is given by 2R/n:

$$(dn_D/dt)/n_D = (dn/dt)/n = \_\ n <\sigma_{DT}\, v> \qquad (2)$$

Assuming for simplicity that DT fuel is held at constant temperature so that $<\sigma_{DT}\, v>$ is constant in time while it burns, Eqn. 2 can be integrated to give

$$n/n_0 = 1/(1+ n_0\sigma_{burn} <\sigma_{DT}\, v>/2) \qquad (3)$$

where $\sigma_{burn}$ is the burn time. Equation 3 can be recast in terms of f, the fractional burnup of fuel, as:

$$f/(1-f) = n_0\sigma_{burn} <\sigma_{DT}\, v>/2 \qquad (4)$$

where $f \equiv 1\text{-}n/n_0$. For complete burnup, the gain would be $G_{max}$= 300 at 10 keV. This is simply the ratio of energy for a 14.1 MeV neutron and 3.5 MeV alpha divided by the 60 keV of thermal energy for a DT ion pair with electrons.

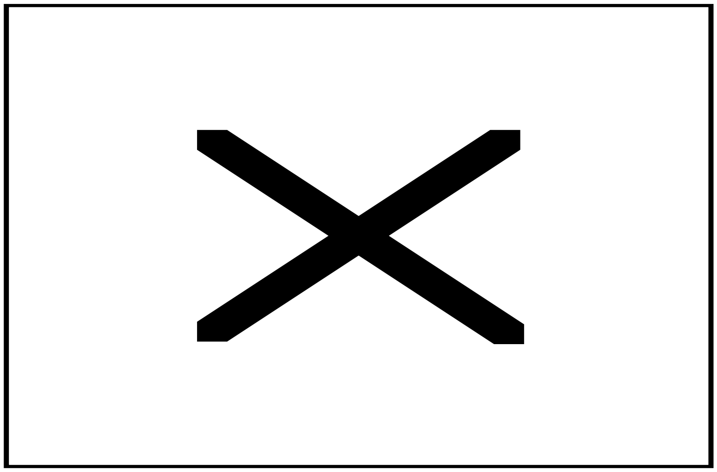

***Figure 1.*** *Fusion energy output relative to plasma energy vs. the product of density and burn time.*

As a function of burn time, the gain plotted in Fig. 1 is $G_{max}$ times the fractional burnup. We can define a Lawson condition using Fig. 1. With $n\equiv_{burn} \sim 3x10^{14}$ $cm^{-3}$ sec the gain relative to thermal energy is around five, enough to allow for net gain with realistic efficiencies. The *net* gain relative to initially stored electrical energy is the gain of Fig. 1 times the efficiency of heating fuel to 10 keV temperature. For example, if 50% of the stored electrical energy is converted to liner kinetic energy [Gerwin 78], and 50% of the liner kinetic energy is converted to thermal plasma energy at peak compression, then the net gain would be 1/4 of the gain plotted in Fig. 1.

A plasma heated to 10 keV will cool by numerous mechanisms. The total power losses per unit volume are conventionally written as $3nT/\tau_E$, where $\tau_E$ is the global energy confinement time. In deriving Fig. 1 we ignored losses, which is equivalent to assuming $\tau_E >> \tau_{burn}$. To obtain the minimum possible system size for the purpose of low–cost development, we would require $\tau_E \sim \tau_{burn}$. That is, if $\tau_E$ were much less than $\tau_{burn}$ the fuel would cool before it burned. On the other hand if $\tau_E$ were much larger than $\tau_{burn}$, the plasma should be made smaller to equalize the two, which requires less energy, assuming the energy confinement time increases with system size. For approximate estimates, the relevant energy confinement time and the burn time should both satisfy a Lawson-like $n\tau$, which we will take for the purposes of demonstrating feasibility to be the same as ITER, and approximately an energy breakeven condition according to Figure 1:

$$\text{Lawson requirement:} \quad n\tau \sim n\tau_E \sim n\tau_{burn} \sim 3x10^{14}\ cm^{-3}\ sec$$

This $n\tau_E$ corresponds to 1.5% burnup fraction in a pulsed system.

## B. Pressure of High-Density Fuel Dictates Pulsed Technology

The first requirement for containing fuel is equilibrium or pressure balance to prevent the fuel from expanding during the required burn time. There are a continuum of possibilities ranging from ICF with zero magnetic field where pressure is supported by the inertia of surrounding low-temperature fuel, to full magnetic confinement where plasma pressure is less than or equal to the confining magnetic pressure. In the MTF regime we consider the possibility where plasma pressure is larger than or equal to the magnetic field pressure, because the main role of magnetic field is insulation and not confinement.

Broadly speaking, the relevant technology changes as the density increases. We assume Ti ~ Te ~ 10 keV. At densities from $10^{14}$ cm$^{-3}$ up to about $10^{16}$ cm$^{-3}$ plasma pressure can be contained by superconducting magnets, where the higher density corresponds to magnetic confinement with $\beta = 1$. Plasma $\beta \equiv 2nkT/(B^2/8\pi)$, where B is the magnetic field. At pressure or density too high for superconductors, pulsed magnets can be used up to pressures that fracture known materials. Strength limitations set an upper limit on the density at about $10^{18}$ cm$^{-3}$. This density corresponds to magnetic field of about 1 MG if magnetic pressure confines the plasma. To date, the largest magnetic fields reported are pulsed fields of about 20 MG, which can be obtained by imploding liners [Pavlovskii 96]. If 20 MG were used for plasma confinement, the corresponding maximum density is around $10^{21}$ cm$^{-3}$. Above that density, plasma pressure must be held by the inertia of material walls, although magnetic field can be utilized for its insulating properties. For ICF the density of the ignited hot spot is expected to be about $10^{25}$ cm$^{-3}$, which corresponds to a pressure of 200 Gbar. We see that the technology for fusion changes radically as one moves from MFE density to ICF density.

## C. Fusion Fuel Diffuses Before Burning

Another basic point useful to recall for the following discussion is that $\sigma_{DT}$, the cross section for fusion, is much smaller than $\sigma_C$, the cross section for Coulomb scattering, almost independent of density. By definition the frequency of collisions is given by the product of cross section and flux. The rate of fusion reactions is given by the right–hand side of Eqn. 3:

$$\text{Frequency of fusion reactions} = \_\ n \langle \sigma_{DT}\, v \rangle \qquad (5)$$

The effective fusion cross section can be taken as $\langle \sigma_{DT}\, v \rangle / v_i$, ~ 1 barn ($10^{-24}$ cm$^2$) at 10 keV where $v_i$ is the ion thermal speed. Similarly the Coulomb collision frequency can be written as a product of the Coulomb cross section and particle flux, n multiplied by $v_i$:

$$\text{Ion-ion Coulomb collision frequency} = \nu_{ii} = 1/\nu_{ii} = n\, v_i \nu_C \qquad (6)$$

Thus at 10 keV and $10^{14}$ cm$^{-3}$ $\nu_C$ ~ 7000 barns. This Coulomb collision frequency, or reciprocal of the ion-ion collision time, is extensively discussed in the standard textbooks. Because of the accumulated effects of small-angle scattering, the frequency of Coulomb collisions is proportional to $\ln\Lambda$, a factor that depends weakly upon temperature and density. The Coulomb logarithm is often taken as a constant about equal to 20, but even for rough estimates we will calculate $\ln\Lambda$ when it arises, because the range of density we will consider ($10^{14}$–$10^{26}$ cm$^{-3}$) corresponds to $\ln\Lambda$ changing by more than a factor of 3.

At a temperature of 10 keV, the cross section or frequency for Coulomb scattering is larger than the cross section or frequency of fusion reactions by a factor of 2000-6000 for density between $10^{26}$ cm$^{-3}$ and $10^{14}$ cm$^{-3}$ respectively. Therefore, the number of collisions (N) that occur during a burn time is calculated to be:

$$N = \tau_{burn} / \tau_{ii} = 2\, f\, v_i \tau_C / \langle\sigma_{DT}\, v\rangle \tag{7}$$

For $n\tau_E = 3\text{x}10^{14}$ cm$^{-3}$ sec, the burn time is between 60 and 180 ion-ion collision times as density varies from $10^{26}$ cm$^{-3}$ to $10^{14}$ cm$^{-3}$.

In summary, we conclude that, *independent of the fuel density over a wide range of density*, collisional diffusive processes are unavoidable when fusion fuel is assembled for a time long enough to produce energy gain.

**D. The Nature of Energy Diffusion**

Even if fuel is held in pressure balance for the necessary burn time, it has been historically difficult to achieve the required global energy confinement time. Much of MFE fusion research has been devoted to understanding the many modes of plasma motion that transport energy in addition to classical collisional processes. With ICF, there is less uncertainty about loss processes, because the absence of a magnetic field simplifies the transport physics. In that case electron thermal conduction is the dominant loss process. In the ICF approach parameters are chosen so that even electron thermal conduction is consistent with the Lawson condition. One could say that ICF is the "worst case" for thermal losses when compared with any type of magnetic configuration.

***Classical diffusion.*** We review now the lower bound on energy confinement represented by classical diffusion. In MFE fusion literature, the global energy confinement time is usually expressed in terms of thermal diffusivity:

$$\tau_E \sim a^2/\chi, \tag{8}$$

where $a$ is the characteristic dimension across which heat diffuses and $\chi$ is the thermal diffusivity. The value of $\chi$ (same as thermal conductivity divided by density) is derived by calculating the energy flux in the presence of a temperature gradient.

Thermal diffusion can also be viewed as a random walk of particles. After each collision, a particle moves one step at random either up or down the temperature gradient. Heat conduction is the diffusion of cold particles up the gradient and hot particles down the gradient with no net flux of particles. The essential feature of the random walk is that after N collisions, there is a binomial distribution for particle location, and it has a width proportional to $N^{1/2}$. If the step size is $\lambda$, then the standard deviation of the distribution of particle locations after N collisions is $a$ given by

$$a = N^{1/2}\, \lambda. \tag{9}$$

If the collision time is $\tau$, the number of collisions is $N = t / \tau$, so we can also write Eqn. 9 as

$$t = (a/\lambda)^2 \lambda \tag{10}$$

Eqn. 9 indicates that if N collisions are needed before heat dissipates, then the fuel must have a characteristic size greater than *a*. Equivalently, Eqn. 10 gives the time to dissipate heat (energy confinement time) in terms of the number of steps across the characteristic size, (*a*/_), and the time per step or collision time.

***Classical diffusion without a magnetic field.*** To apply the random-walk argument to electron thermal conduction, we equate the step size to a plasma mean free path $\lambda$. Electrons have a larger thermal speed and a shorter collision time, such that the mean free path $\lambda$ is the same for either ions or electrons:

$$\lambda = 1 / n\tau_C = v_i \tau_{ii} = v_e \lambda_{ee} \tag{11}$$

where $v_{i,e}$ is the ion, or electron, thermal speed. Electrons collide more frequently by a factor of $(m_i/m_e)^{1/2}$, or about 60 for a DT mixture. Therefore, if we consider high density where ions make about 60 collisions, then electrons make about 3600 collisions during the fusion burn time. The size of a plasma with burn time long enough to allow 3600 electron-electron collisions is

$$a = (3600)^{1/2} \lambda. \tag{12}$$

For ICF, where the ignition hot spot density is about $10^{25}$ $cm^{-3}$, the mean free path is 0.7 microns; this simple estimate of Eqn. 12 for hot spot radius is 42 microns. More detailed calculations [Lindl 95] give about the same value.

***Classical diffusion with a magnetic field.*** To apply the random-walk argument to magnetized plasma is more difficult, because the step size depends upon complicated particle orbits in the magnetic field. However, for poloidal-field dominated configurations like the Reversed Field Pinch, the spheromak, and the Field-Reversed Configuration (FRC), and for tokamaks, detailed studies give the simple prescription that the step size can be taken as the ion gyro radius calculated in the poloidal magnetic field [Boozer 83]. (In a torus the toroidal direction is the long way around the torus, and the poloidal direction is the short way around.) In the direction perpendicular to a magnetic field, the classical ion heat conduction dominates because the ions have a larger gyro radius. Therefore, we can estimate that the minimum required size of a fusion system to diffuse heat slowly enough to meet Lawson, say 180 ion-ion collision times, is

$$a = (180)^{1/2} r_i, \tag{13}$$

where $r_i$ is the ion gyro radius in the poloidal magnetic field. The tokamak banana-regime formulas for neoclassical transport theory give about 20 $r_i$ instead of the approximate estimate of 13 $r_i$ given by Eqn. 13. Because of anomalous transport, the design radius of ITER is about 5 times larger than the neoclassical limit (i.e. $a_{iter} \cong 100\ r_i$).

**E. Characteristic Step Sizes Decrease as Density Increases**

Comparing Eqns. 8 and 10, we see that $\chi$ has the form of a step size squared times a collision frequency. For classical transport,

Electron thermal conduction: $\chi_e \sim \chi^2 \chi_{ee}$. (14)

Ion cross field transport: $\chi_i \sim r_i{}^2 \nu_{ii}$. (15)

The mean free path ($\lambda$), which depends on temperature and density, is plotted in Fig. 2 for 10 keV temperature. The gyro radius ($r_i$), which depends mainly on density, is also plotted in Fig. 2, assuming constant poloidal beta ($\beta_i$), where $\beta_i$ is the ratio of ion pressure to poloidal field pressure ($\beta_i = 8\pi nkT_i/B_p{}^2$). The density dependence can be seen by writing the gyro radius as:

$r_i = v_i/\omega_{ci} = (c/\omega_{pi})\beta_i{}^{1/2}$ (16)

where $\omega_{ci}$ is the ion cyclotron frequency in the poloidal magnetic field, c is the speed of light, and $\omega_{pi}$ is the ion plasma frequency,

$\pi_{pi} = (4\pi ne^2/m_i)^{1/2}$ (cgs units). (17)

Poloidal beta in tokamaks and the above mentioned configurations is observed not to differ much from unity.

In the spirit of a survey of minimum system size for fusion, Fig. 2 gives useful guidance. The dimensions of a system without magnetic insulation become unacceptably large at low density. The classical limit for the size of a magnetized plasma is seen to be quite small as density increases. If the anomaly factor assumed in the ITER design, and observed with tokamaks having density in the vicinity of $10^{14}$ cm$^{-3}$, were to apply at higher density, then Lawson should be possible at $10^{20}$ cm$^{-3}$ in a tokamak with a minor radius of 2.8 mm! This dramatic reduction in size at higher density provides much of the motivation for MTF.

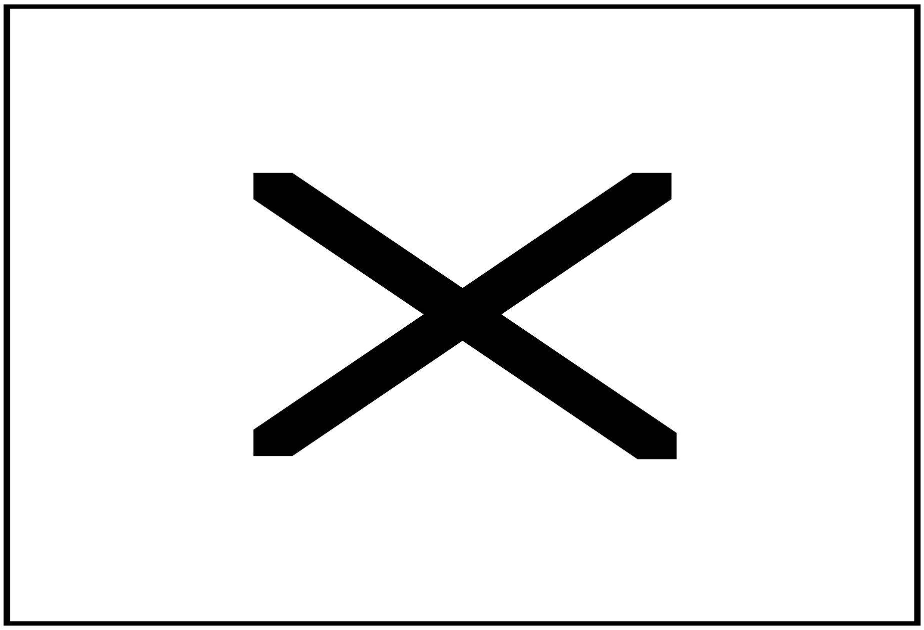

***Figure 2***. *Plots of characteristic step sizes and poloidal magnetic field strength assuming poloidal beta = 1 vs. fuel density for a plasma with 10 keV temperature.*

***Speculation on anomalous transport.*** Anomalous transport mechanisms are still a subject of unfinished research. Clearly, all possibilities cannot be anticipated, but the following can be noted. Generally the form of $\chi$ is a product of characteristic lengths times a frequency. The characteristic lengths in a plasma normally identified are $\lambda$, $\lambda_D$, $c/\omega_{pi}$, $c/\omega_{pe}$, $r_i$, and $r_e$. As already noted, $c/\omega_{pi}$ and $r_i$ are only different by a factor of order unity, and therefore the gyro radius in Fig. 2 is also approximately the same as $c/\omega_{pi}$. The gyro radius $r_e$ (and thus $c/\omega_{pe}$) is smaller than the gyro radius $r_i$ by a factor of $(m_i/m_e)^{1/2}$. The Debeye length $\lambda_D$ has the same density dependence as the electron gyro radius. Therefore the variation of all the usual characteristic lengths with density is correctly inferred from Fig. 2, and a reasonable conjecture is that the tendency towards smaller size at higher density is true for anomalous transport as well as for classical transport.

## III. Plasma Energy Reduced at High Density

To quantify the variation of diffusion step sizes with density in terms that come closer to economic value, we show in Fig. 3 the thermal energy contained by a plasma with characteristic dimension of *a*. Three different configurations are included in Fig. 3: ICF-relevant unmagnetized fuel, tokamaks, and a generic MTF plasma taken to be a compact torus (CT). We assume that when density is varied for a given configuration, size is adjusted to be the minimum necessary to provide $n\tau_E = 3\times10^{14}$ cm$^{-3}$ sec at 10 keV temperature. Specific assumptions for each configuration are summarized in the table following Fig. 3.

### A. ICF Energy Requirements

For ICF we see a very strong dependence of energy upon density, and thus the importance of compressing to high density. By compressing to density of approximately $10^{25}$ cm$^{-3}$, the energy in the hot spot according to Fig. 3 is approximately 30 kJ, which is similar to the value anticipated in the design of NIF [Lindl 95]. Achieving such a high density requires an implosion velocity of about 30-40 cm per microsecond and a radial convergence of between 30 and 40. The NIF laser design, with 1.8 MJ and 500 TW, has enough energy and power to produce these conditions even with the inefficiency of indirect drive. However, if the hot-spot density were to be reduced, the energy requirements would be considerably increased as shown in Fig. 3, and the power requirements would also be increased to achieve the same $n\tau_E$. Thus, the ICF approach utilizes very high density to achieve fusion with minimum energy, but the driver requirements are extremely demanding and expensive.

## B. Tokamak Energy Requirements

Tokamaks are included in Fig. 3 for academic interest, even though high-density operation of a tokamak-like configuration is not being considered. The poloidal magnetic field required at any given density is plotted in Fig. 2. For the assumed value of safety factor ($q$) and aspect ratio, the toroidal field required would be approximately a factor of ten higher than the poloidal field. Thus, the magnetic energy would be 100 times as large as the plasma thermal energy plotted in Fig. 2. The cost of a tokamak is well known to be strongly tied to the cost of the magnets.

The important aspect of the tokamak is that much more is known about transport than for any other configuration. A useful summary of tokamak transport formulas can be found in the textbook by Kadomtsev [Kadomtsev 92]. We plot both the classical limit for confinement (neoclassical in the banana, transition, and Pfirsch-Schluter regimes as density increases) and some empirically based models for anomalous transport. The anomalous transport curves show the anticipated tendency that system size becomes small at increasing density. One concludes from these plots that if the technology were available to operate tokamaks at higher density, the size and cost could be reduced.

### C. MTF Energy Requirements.

For MTF compression by a liner, there are many possible magnetic configurations. To make estimates for Fig. 3, we have chosen a compact toroid (CT) plasma as generic for any magnetic configuration. Specifically the CT curves in Fig. 3 are calculated assuming the plasma is an FRC, which has ideally only poloidal magnetic field [Tuszewski 88]. Similar values apply to a spheromak. In that case a toroidal field comparable in magnitude to the poloidal field of the FRC would be required [Jarboe 94]. CTs require more energy than a tokamak at a given density because CTs need more volume to achieve the same effective radius or insulating distance. A prolate FRC, as is commonly studied in experiments, has an effective radius equal to the distance from the field null to the outer edge, which is approximately 0.3 of the small radius of the prolate spheroid. Thus the FRC estimate for energy may be conservatively high in Fig. 3, although modeling of wall-plasma interactions tend to show spatial profiles that resemble an FRC-like profile (Siemon 97).

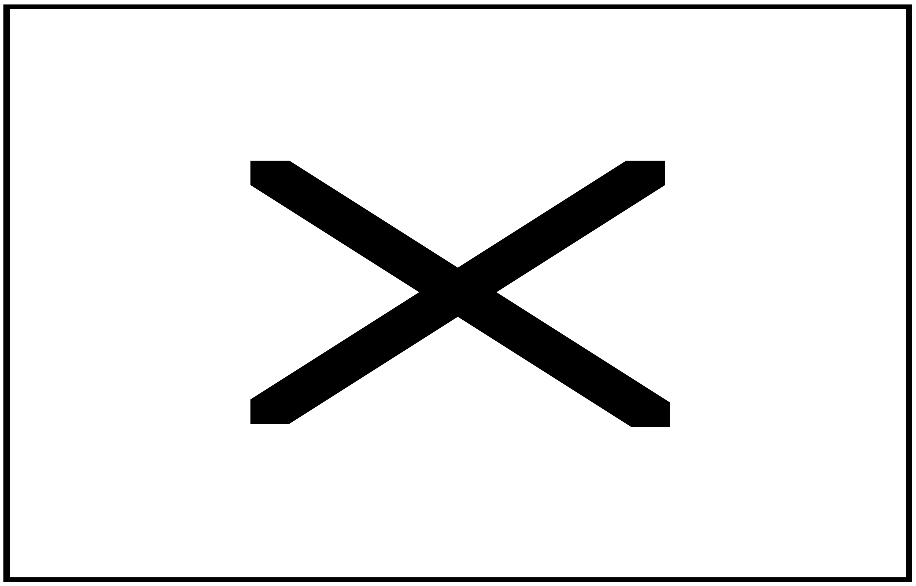

***Figure 3***. *Energy requirements vs. fuel density for various configurations and transport assumptions assuming* $n\tau_E = 3x10^{14}$ $cm^{-3}$ *sec,* $T = 10$ *keV, and poloidal* $\beta = 1$.

| **Configuration** | **Transport** | **Comments** |
|---|---|---|
| ICF | Electron thermal conduction | Spherical plasma with size given by Eqn. 12. Density of ~$10^{25}$ $cm^{-3}$ corresponds to NIF. |
| Tokamak | Neoclassical, anomalous neo-Alcator, and anomalous ITER-89P | Aspect ratio (2.9), poloidal beta (1.0), and safety factor q (3.0) are held constant at ITER-like values. |
| Compact Torus (CT) | Classical or Bohm | Geometry of a prolate FRC assumed for illustration with length to diameter ratio of 3. |

The amount of energy required for fusion conditions depends upon the global energy confinement time. Fig. 3 indicates that compressed plasma energy between about 30 kJ and 10 MJ is required in the MTF regime (density of $10^{20}$ $cm^{-3}$), if plasma transport is between classical and Bohm. For the larger Bohm requirement of 10 MJ, the required liner kinetic energy would be tens of MJs, a few times the final plasma energy. One striking difference between the MFE and MTF regimes of density is that Bohm is an acceptable possibility at MTF density, while as shown in Fig. 3, Bohm is totally unacceptable at $10^{14}$ $cm^{-3}$.

**D. Comments on Bohm Diffusion**

The curve labeled Bohm deserves additional comment. In the early days of fusion research Bohm was introduced as an empirical diffusivity [Spitzer 62] equivalent to the following:

$$\omega_{BOHM} = \omega_i\,(\omega_{ci}\tau_{ii})/16, \tag{18}$$

where $\lambda_{ci}\lambda_{ii} = \lambda/r_i$ is the magnetization parameter. The factor of 16 has no theoretical basis. It is interesting to note that apart from the factor of 16, $\chi_{BOHM}$ is the geometric mean or logarithmic average of $\chi_i$ and $\chi_e$ given in Eqns. 14 and 15. Thus Bohm can be thought of as intermediate between classical magnetized and unmagnetized confinement. Kadomtsev describes how there are situations where macroscopic convection can lead to energy transport with a global Bohm confinement time [Kadomtsev 92]. Studies of wall-confined MTF-type plasma by Vekshtein show how classical confinement can lead to a Bohm-like scaling [Vekshtein 90]. Even more interesting is that experimental data from a number of carefully studied magnetic configurations, including Reversed Field Pinches, spheromaks, and FRCs, is generally as good as Bohm or better.

Global energy confinement time can be worse than Bohm when other non-diffusive processes dominate. Examples are radiation because of impurities, or plasma flow out of the system at a speed comparable to the thermal speed. Radiation by impurities is always a concern and places an upper limit on the allowed impurity concentration. Plasma flow cannot be ruled out in general, but the conjecture here is that target plasma configurations can be found for which a pressure equilibrium exists between the metal liner boundary and the fuel, and thus flow is reduced to nothing worse than convective motions. Close proximity of a conducting boundary should provide a stabilizing influence on magneto-hydrodynamic modes, especially since magnetic fields do not penetrate a conducting boundary on the short time scale of interest for MTF. Spheromaks and FRCs are two examples of CTs for which there are data to support this conjecture. We conclude Bohm represents a reasonable, even conservative, expectation for achievable global energy confinement based on previous experimental results, assuming impurities can be avoided by careful experimental technique.

## IV. The Size and Cost of Ignition Facilities

Only a rough connection can be made between cost and plasma energy plotted in Fig. 3. For each of the configurations, however, one would expect that the indicated reduction of energy as density increases would result in a reduction of costs for the required facility to create the ignition-grade plasma. Even an approximate connection is adequate for present purposes, given the many decades of system size plotted in Fig. 3. Note that the left-hand scale varies by 12 orders of magnitude. We list in Table 1 costs for recently designed ignition-class facilities in each of the regimes of MFE, ICF, and MTF.

In the case of MTF we base the cost for an ignition facility upon the ATLAS pulsed-power facility, recently designed and under construction by Defense Programs at Los Alamos [Trainor 97]. ATLAS should be able to deliver 5-10 MJ to an imploding liner, which makes it suitable for a considerable range of possible MTF experiments. Although the primary mission of ATLAS is not MTF, a reasonable number of additional experiments to test MTF are consistent with current plans for the facility. For the purpose of estimating MTF ignition-grade facility costs, we assume that 1) the 35-MJ of stored energy in ATLAS is enough to implode a liner-plasma configuration to ignition (see Fig. 3), and 2) the additional cost for the plasma target preparation is small compared with the $50-million cost of the ATLAS facility. The purpose of Table I is to compare facility costs needed for a fusion energy development program. The fact that ATLAS is being built for other reasons is simply a fortunate circumstance. The research effort expended to date on MTF has been minuscule compared with the other two approaches to fusion, and so the cost of achieving ignition conditions is obviously much less certain. However, the advantage appears so large that the accuracy of the estimate is not very important.

## Table 1. Approximate Cost of Ignition Facilities

| Concept | Plasma Thermal Energy | Facility Cost |
|---|---|---|
| MFE/ITER | 1 GJ | $10 billion |
| ICF/NIF | 30 kJ | $1 billion |
| MTF/ATLAS | ~ 10 MJ | ~$50 million |

## V. Near Term Prospects for MTF Research

### A. Typical MTF Parameters

The main points of this paper, which are contained in Fig. 3 and Table 1, argue for starting a new thrust in fusion energy research. In this section we discuss some aspects of how to begin that effort. Our concept for a liner-driven plasma implosion suggests approximate values for initial and final plasma parameters as given in Table 2.

Table 2. Representative Conditions for an Adiabatic Implosion

| Parameter | Desired Final Conditions | Required Initial Plasma if $K_v$=100 | Required Initial Plasma if $K_v$=1000 |
|---|---|---|---|
| Temperature | 10 keV | 460 eV | 100 eV |
| Density | $10^{20}$ cm$^{-3}$ | $10^{18}$ cm$^{-3}$ | $10^{17}$ cm$^{-3}$ |
| B Field | 10 MG | 100 kG | 100 kG |
| Liner inner radius | 5 mm | 5 cm | 5 cm |

To illustrate the required initial target-plasma conditions, we assume adiabatic compression ($pV^{\gamma}$=const) with a volumetric compression $K_v$ = 100 or 1000, corresponding to cylindrical, or spherical, radial compression of 10 respectively. The adiabatic approximation is justified according to time-dependent calculations taking thermal and radiation losses into account [Lindemuth 83], and the parameter space for MTF is found to be quite large, assuming an implosion velocity on the order of $10^6$ cm/sec.

### B. Target Plasma Possibilities.

Among the many possible magnetic configurations that would be possible for the target plasma, the ones currently receiving attention in our awareness are: 1) the MAGO-type of accelerated diffuse-z-pinch plasma [Lindemuth, 96], 2) an expanded high-density-fiber z pinch inside a conducting boundary [Wysocki 97], and 3) compact toroids [Ryutov 96]. An approach that uses energy from a high-power e-beam driver to form a magnetized plasma has also been reported [Chang 78].

Extensive research on compact toroids, the spheromak and Field-Reversed Configuration, began in about 1980. The review articles by Tuszewski and Jarboe have hundreds of references [Tuszewski 88, and Jarboe 94]. By definition, a CT is a self-contained magnetized plasma that can be moved from one spatial location to another. Thus, CTs are an obvious candidate for inserting a plasma target into an imploding metal liner. Unfortunately, most fusion-related liner research ended about the same time that CT work began, so most of the information gained from CT research was not available to the early liner researchers. A few experiments studying the implosion of an FRC-type of CT were done in Russia [Kurtmullaev 82]. Most CT research was done at much lower density than is needed for MTF. The RACE experiments at LLNL are a notable exception [Hammer 91]**.** There is no obvious problem in forming CTs at higher density, and experiments to move in that direction would be desirable.

The MAGO and expanded fiber z pinch are diffuse z-pinch magnetic configurations. The outstanding attraction of these approaches is that the technology for plasma formation is reasonably compatible with liner implosion technology, and is less complicated than for CTs. For MAGO at least, plasma density and temperature appear suitable for proceeding with MTF implosion experiments [Lindemuth 95]. More refined measurements are still needed to characterize global energy confinement in both the MAGO and expanded fiber plasmas. The diffuse z pinch has well known limitations with regard to stability, and containment of energetic particle orbits. However, simulations show [Sheehey 89] that an unstable plasma inside a conducting boundary can evolve to a stable state (known as a Kadomtsev-stable profile). In such a state, the energy confinement may be adequate on the time scale of an MTF implosion. The fact that most alpha particles generated near peak compression would be lost is not a major consideration for the batch-burn approach we have assumed for MTF.

### C. Liner Technology and Facilities are Available.

The advances in liner technology of the past few years are impressive [Chernyshev 97]. More than enough liner velocity and implosion symmetry has been demonstrated compared with the detailed requirements for an MTF liner system discussed elsewhere [Lindemuth 96, Siemon 97, Ryutov 96, and Schoenberg 98]. A quasi-spherical implosion of unmagnetized plasma has also been reported [Degnan 96].

A number of existing facilities supported by DOE’s Defense Programs and DOD would be suitable for a variety of MTF experiments. These include the Z capacitor bank at Sandia National Laboratory, the Shiva Star capacitor bank at Phillips Air Force Laboratory, the Pegasus capacitor bank at Los Alamos National Laboratory, the Ranchero explosively-driven electrical generators at Los Alamos, and the ATLAS capacitor bank under construction at Los Alamos.

These facilities and expertise allow significant leveraging of research dollars, which gives additional incentive for MTF research.

### D. Major Technical Issues.

MTF can be conceptually separated into three inter-related aspects: target plasma formation and confinement properties, liner-driver implosion, and target-plasma compression. The major technical issues are:

Issues of Target Plasma Formation and Confinement Properties

- plasma parameters on the proper adiabat for heating to ignition
- suitable magnetic topology for magnetohydrodynamic stability and adequate thermal insulation
- plasma-wall interactions leading to high-Z impurities and concomitant plasma radiation losses

Liner-Driver Implosion Issues

- symmetric implosions of a liner at approximately $10^6$ cm/s (a velocity well within the range of what has been demonstrated in Defense Program experiments).
- development of liner implosion configurations that match target-plasma requirements for a conducting boundary throughout the implosion
- convergence ratios of roughly 10 in a stable quasi-spherical geometry

Target Plasma Compression Issues

- technical compatibility between plasma formation and liner-implosion technologies
- accelerated mixing of wall and plasma material during the implosion, resulting for example from Rayleigh-Taylor instabilities in the liner
- plasma thermal transport during the implosion
- diagnostic methods under conditions of energetic implosions

We recommend a multi-institutional MTF research program to address these important experimental and theoretical questions. In addition, studies are needed on how MTF would best be utilized for electricity generation or other applications. Qualitatively the intrinsically pulsed nature of MTF makes it similar to ICF in its potential application. Early studies of an electrical power plant based on liner technology [Krakowski 78] indicated the basic feasibility of a pulsed liner-driven system, and identified numerous technology issues that must be solved.

An intriguing more recent study of power generation using MHD conversion of fusion energy [Logan 93] indicates that MTF is well matched to the requirements of an MHD conversion system. The energy from 14-MeV neutrons would be used to vaporize and heat a lithium-containing blanket to 1 or 2 eV. Then MHD conversion gives higher efficiency and a greatly reduced balance of plant cost leading to considerably less expensive electricity compared with conventional MFE reactor concepts.

## VI. Conclusions

We briefly reviewed some very elementary features of all the standard fusion approaches. The main assumptions were that the fusion fuel is deuterium and tritium with a 10 keV Maxwellian velocity distribution. We emphasized the variation of quantities with fuel density and observed that the system size becomes small, and energy requirements are much reduced, when fuel density is made considerably larger than in conventional MFE systems. This general conclusion, which has been noted by many researchers in the past, warrants renewed attention today as the fusion program restructures itself within today's budget limitations.

The reasons for embarking on an MTF research effort at the present time are several:

- The cost of development for fusion has become a major consideration in recent years, and MTF appears to offer advantages compared with MFE and ICF.

- The pulsed power facilities of Defense Programs, both DOE and DOD, are remarkably well matched to what is needed to investigate MTF.
- In the twenty years since MTF-like concepts were last seriously pursued in the United States, the theoretical understanding and experimental methods of plasma science as well as the technology of high-energy liner implosions have advanced significantly.

The interesting regime we call Magnetized Target Fusion occurs at fuel density of about $10^{20}$ $cm^{-3}$. The MTF regime may be an optimum in the sense of using the maximum possible magnetic field for insulation of the fuel, and thus the smallest possible system size without going to the extreme density of ICF. This new thrust in fusion research has the potential to achieve the lowest possible development cost.

We believe that the arguments presented here are robust in nature and give a valid basis for recommending a new research thrust in magnetic fusion energy. Given the global importance of long-term energy R&D, adding MTF as a new complementary element to MFE and ICF in the portfolio of fusion approaches seems well justified.

### Acknowledgements

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## APPENDIX B. Other MTF Target Plasmas

In this appendix we briefly review several previous or ongoing MTF target formation efforts:

- Sandia phi-target [Lindemuth81],
- Russian (VNIIEF) MAGO system [Lindemuth95],
- z-pinches utilizing either static gas-fill or exploding fibers [Wysocki97]
- the spheromak type of CT.

### 1. Phi-Target

The phi-target was investigated briefly at Sandia National Laboratory around 1977, during which approximately 39 experiments (discharges) were conducted (Fig. B1). These experiments were unique in that both target-plasma generation and target implosion were performed in the same experiment utilizing a small relativistic electron-beam machine (single beam from the REHYD device). The target package consisted of a 3-mm-diameter spherical shell with a 0.1-mm-thick glass wall or a 0.3-mm-thick polystyrene wall. The capsule had small metal end-caps at both poles. One end-cap was connected to the anode of the electron-beam machine. The other end-cap was connected to a collector-plate outside the capsule, which intercepted the low intensity electron pre-pulse. In some experiments, the interior of the capsule was filled with approximately 100 torr of DT gas, while in other experiments, the interior contained a deuterated polyethylene (CD2) wire 25 to 50 mm in diameter along the symmetry axis and connecting the two metal end-caps.

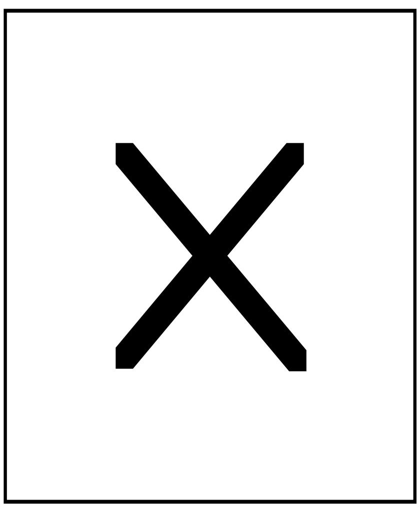

Fig B1. Phi-Target geometry.

The pre-pulse current of electrons rose to between 5 and 15 kA in a ramp over a period of 1 μs. This current was collected by the collector-plate and gave rise to a discharge inside the capsule, which thus preheated and magnetized the target plasma. Two-dimensional MHD modeling indicates that the peak temperature in this target plasma was 21 eV, while the average ion density was $6 \times 10^{18}$ cm$^{-3}$ [Lindemuth81].

The main pulse of 1 MeV electrons had a current of 250 kA and a FWHM of 100 ns. These electrons passed through the collector plate and deposited roughly 4 kJ directly into the wall of the capsule, creating an exploding-pusher implosion of the target plasma. The pusher velocity reached 4 cm/μs giving an implosion time of roughly 40 ns. Diagnostics included Ag activation, neutron time-of-flight, and optical streak data for pusher motion.

Two-dimensional MHD modeling indicates a peak temperature of 362 eV at a radial compression ratio of 15, an average density of $1.7 \times 10^{22}$ $cm^{-3}$, and an expected neutron yield of $10^6$. Neutron yields in the range of $5 \times 10^6$ to $3 \times 10^7$ were observed in 7 of the 15 experiments where the target package was "complete." For the remaining roughly 24 experiments, some aspect of the target package was purposefully "damaged," *i.e.*, half the spherical shell was missing, or there was no gas or polyethylene wire present to form the target plasma, or the collector-plate was missing, or the electron pre-pulse was effectively eliminated. In every one of these "damaged" experiments, the neutron yield was less than the detection threshold of $1 \times 10^6$. Since only "complete" target packages produced a neutron yield, there is reasonable evidence that the neutron production is truly thermonuclear and the system is behaving reasonably like the 2-D MHD calculations.

An interesting aspect of these phi-target experiments is the very small energy content in the target system, due to the small size of the target and relatively low intensity of the electron-beam driver. After the preheat phase, the target-plasma thermal energy content is less than 0.4 J. The calculated work done by the pusher at a radial compression of 15 is only 19.5 J, of which 7.7 J remained as an increase in plasma thermal energy, giving a total of 8.1 J. The other 11.8 J is lost to radiation and thermal conduction. For comparison, a typical Nova ICF capsule at peak compression has roughly 600 J of plasma thermal energy, 75 times as much as the phi-target experiments.

**2. MAGO**

While the phi-target experiments represent a low-end in energy content, the Russian MAGO experiments [Lindemuth95] represents the present high-end of energy content for MTF target plasmas. The MAGO device, (Fig. B2) is typically powered by a high-explosive driven electrical generator (EMG) that produces a slow rising current to roughly 2.7 MA, followed by a fast rising current to approximately 7-8 MA in 2-3 μs.

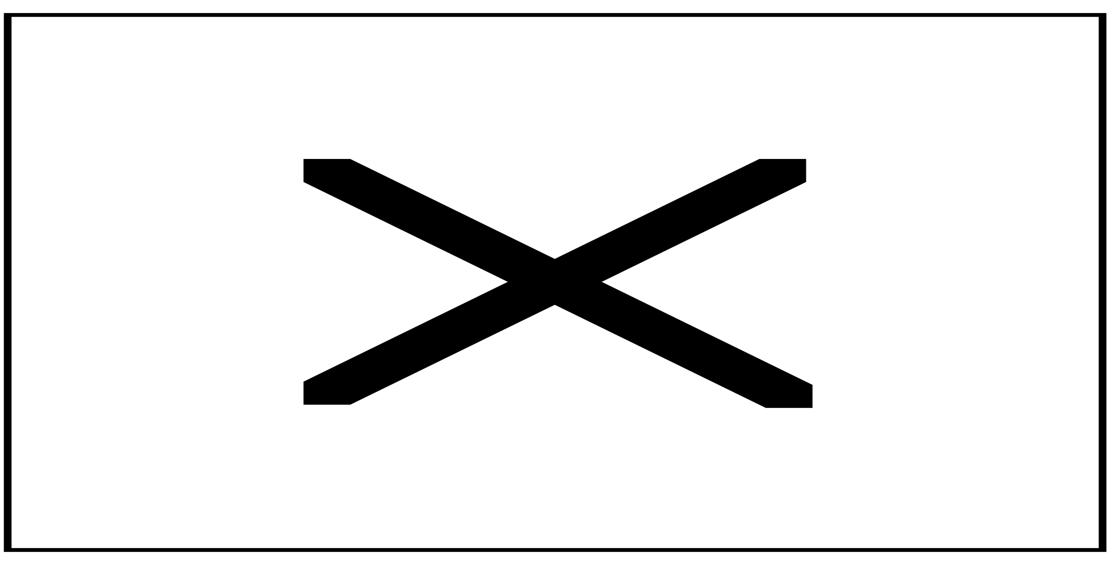

Fig. B2. MAGO chamber.

The typical plasma chamber is cylindrical with a 10 cm radius, roughly 8 cm in length, and has a conducting 1 cm radius center-rod that carries the slow rising 2.7 MA of current. The fast rising current drives a complicated dynamic plasma motion in which an inverse-pinch plasma starting in a neighboring chamber is driven through a nozzle region connecting the two chambers at the outside diameter.

Personnel from LANL have collaborated with VNIIEF personnel in diagnosing the resulting target plasma from four experiments, two performed at VNIIEF and two performed at LANL during the years 1994 to 1995. In summary, over $10^{13}$ D-T neutrons are produced as a result of forming the target plasma, plasma density is approximately $6x10^{17}$ $cm^{-3}$, and the plasma temperature reaches over 200 eV for a period of 2-3 µs. Unfortunately, the harsh environment for the diagnostics has so far prevented a measurement of the plasma cooling time, and the plasma temperature after the initial hot period is experimentally unknown at this time. The peak plasma thermal energy content is estimated to be at least 50 kJ. More recently, VNIIEF has begun experiments with smaller chambers and smaller EMG drivers that are cheaper and allow more frequent experiments. Also VNIIEF now has a capacitor bank system operational that can deliver roughly 3 MA of current to a MAGO chamber, allowing even more frequent experiments. LANL personnel are expected to make measurements on these systems in the summer of 1998. At this time, the MAGO target plasma has not been imploded.

### 3. Z-Pinch Target

Target plasma experiments have been performed on the Colt facility at LANL since 1996 using a z-directed current through plasma contained in a conducting chamber. Colt can produce a drive current of 2 MA rising in 2.5 µs. Experiments have been performed where the plasma chamber and connecting power flow region are statically filled with deuterium gas prior to the discharge. In addition, an exploding fiber approach is being studied, where the discharge current is driven through a cryogenically frozen 200 µm diameter deuterium fiber. The initial small diameter plasma will go unstable and "explode" and heat from instability heating. In less than 1 µs, the plasma expands to the conducting wall and becomes wall stabilized. By the time of peak drive current, 2-D MHD calculations indicate a peak plasma temperature of up to 350 eV is possible, at an average density of roughly $1x10^{18}$ $cm^{-3}$. Data from static gas-fill discharges show that the plasma density in the plasma chamber rises to over $1x10^{18}$ $cm^{-3}$. Magnetic pickup probes at the wall and fast framing camera pictures of the plasma indicate that the plasma is quiescent after an initial roughly 0.4 µs unstable period. An array of filtered soft x-ray diodes indicates that the hot plasma lasts roughly 6 µs. While not conclusive, the x-ray diode data indicates a peak temperature of roughly 70 eV. The performance of these static gas-fill discharges is limited by the fraction of the drive current actually delivered to the plasma chamber region. Because the power-feed region is also gas filled, 60-80% of the drive current remains in this region. It is hoped that this problem will be solved with the cryogenic fiber approach.

### 4. Spheromak Target

The spheromak is another form of compact toroid that could be used as an MTF target plasma. In the context of “traditional” MFE, the spheromak has been studied beginning around 1979, and is reasonably well understood [Jarboe94]. We have considered the possibility of extending the operating parameters to achieve conditions relevant to MTF. The spheromak target plasma would be contained in a cylindrical conducting metal containment region with a 3-cm radius and a 3-cm height. The expected plasma parameters are based on scaling results from the LANL CTX spheromaks in both 61 cm radius (62 cm height) and 28 cm radius (28 cm height) containment regions. Plasma temperature of 130 eV and plasma density of $4x10^{13}$ $cm^{-3}$ were obtained from the 61 cm CTX spheromak [Wysocki90], and temperature and density of 350 eV and $4x10^{14}$ $cm^{-3}$ from the 28 cm CTX spheromak [Jarboe90]. Based on these data, we estimate that a spheromak with an initial toroidal plasma current of 2.8 MA could ohmically heat a plasma with a density of $3x10^{17}$ $cm^{-3}$ to roughly 400 eV in 1-3 μs. The e-folding decay time of the resulting hot uncompressed plasma is estimated at 5-16 μs. A spheromak MTF target like that described here is compatible with a quasi-spherical liner implosion like those performed at the Shiva-Star facility at the AFRL [Degnan95].

A spheromak of this size with a toroidal plasma current of 2.8 MA has an initial magnetic energy content of 26 kJ. Previous CTX spheromaks had this level of magnetic energy content, but were much larger in size. We have considered the required spheromak injector parameters needed to generate an MTF relevant spheromak. Based on previous data [Barnes86, Barnes90], a magnetized plasma gun with an inner electrode radius of 1.34 cm and an outer electrode radius of 2.14 cm, coupled with a gun bias flux of 4.9 mWb, a gun current of 1.3 MA, and a gun voltage of 21 kV is expected to generate the spheromak parameters desired.

For further information on the possibilities and parameter space of a spheromak MTF target, see the following URL: http://fusionenergy.lanl.gov/

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## APPENDIX C: Theory of Wall-Plasma Interactions

This appendix discusses physical considerations important to confining a plasma directly by the liner wall. The first section (by D. Ryutov) gives an overview of the problem, and the second section (by P. Parks) offers another perspective on the issues that are likely to arise during MTF implosions.

### 1. The physics of a wall confinement of a plasma with $\beta$ >>1.

In this section, we present a brief summary of the theory of the wall confinement. A complete description of the problem would have required not a few pages but a few hundreds of pages - a task that goes far beyond the scope of the present document. Here we are simply going to identify some key phenomena governing the wall confinement.

Let a hot dense plasma with initially uniform magnetic field embedded into it get in contact with a material wall parallel to the magnetic field. Let the wall be perfectly conducting (we will discuss variations caused by the finite wall resistivity later). Assume first that the initial plasma beta is not very high, $\beta$ < 10-20. When the cooling of the plasma adjacent to the walls begins (because of the heat losses to the wall), compression of this layers occurs and plasma starts to flow towards the wall, advecting the magnetic field. The magnetic pressure near the wall grows and reaches the value approximately equal to the plasma pressure in the center. The compression ratio of the magnetic field and the plasma is $\sim\sqrt{\beta}$. On can mention parenthetically that the cold dense plasma filling this zone (and having the pressure much less than magnetic pressure) may have a favorable effect on the stability of the system.

The confinement in this mode remains similar to a traditional magnetic confinement, just the strong magnetic field near the walls is created by the plasma itself. Let's denote by $\Delta$ the thickness of the layer with a high magnetic field. According to our previous discussion, $\Delta \sim R/\sqrt{\beta}$, where $R$ is a plasma radius. In the simplest model where the thermal conductivity $\kappa$ is a constant, the heat flux through the layer is $\sim 2\pi R\kappa T/\Delta$, whereas the heat content per a unit length of a plasma column is $\pi R^2 nT$. This yields the following estimate for the confinement time:

$$\tau \sim \frac{R^2}{\chi\sqrt{\beta}}, \qquad (1)$$

where $\chi \sim \kappa/n$ is the thermal diffusivity. In a general case, the dependence of the confinement time on $\beta$ is determined by the dependence of the thermal conductivity on the plasma parameters.

With $\chi$ increasing, new elements in the picture emerge. First, the thickness of a transition layer may become comparable with the skin-depth $\delta$. This effect becomes important at

$$\beta > (R/\delta)^2, \qquad (2)$$

with the skin depth evaluated for the confinement time (1). When the inequality (2) is satisfied, the faster advection of the plasma with the embedded magnetic field will occur, and the confinement time will decrease compared to the estimate (2).

Second, at higher betas, the plasma radiation from the dense layer may become important (because the radiation losses per unit plasma volume scale as $n^2$). The natural boundary for this effect to become important can be evaluated from the following considerations. The characteristic density and the temperature in a dense layer scale as $\sqrt{\beta}$ and $1/\sqrt{\beta}$ with respect to their values in the plasma core. Assuming that radiation losses scale as an inverse square root of the temperature, one finds that the radiation power per unit volume of the dense layer is

$$q_{cold} \sim \beta^{5/4} q, \tag{3}$$

where $q$ is the same quantity for the plasma core. Radiation heat losses from the dense layer, per unit length of the plasma column, are: $2\pi R\Delta q_{cold}$. Imposing the constraint that the radiative losses are smaller than conductive losses, $\pi R^2 nT/\tau$, with $\tau$ as in estimate (1), one finds that radiative losses are insignificant if

$$\tau_{rad} > \tau\beta^{1/4} \tag{4}$$

where $\tau_{rad}$ is the radiative cooling time for the parameters of a plasma core (approximately 30 times longer than the Lawson time for Q~1). At higher betas, the confinement time will be smaller than according to estimate (1).

At very high betas and a poorly conducting wall, a regime where the diffusive scaling is replaced by the advective scaling sets in: the radiative cooling, in combination with the leak of the magnetic field into the wall, causes continuous plasma flow toward the wall, where the DT plasma cooled to temperatures ~0.5 electronvolt becomes, in a sense, a part of the wall. In this regime, the confinement time depends on $R$ not quadratically but only linearly.

An interesting feature of the wall confinement of a high-beta plasma is that the transitional layer is virtually impermeable to the impurities: first, the thermal force in a high beta plasma is directed in such a way as to repel impurities from the hotter plasma; second, there is a plasma flow towards the walls. It goes without saying that, at the plasma parameters of interest for MTF, the direct penetration of neutral atoms from the wall is limited to distances of a few micron.

The actual value of the transport coefficients in the magnetized region, where both $\nu_i/\omega_{Ci}$ and $\nu_i/\omega_{Ci}$ are much less than 1, is almost certainly determined by drift-type microinstabilities. They can hardly result in the transport coefficients exceeding the Bohm diffusion coefficient. In the case of a high enough density, Bohm losses are compatible with the required confinement time, and the need in the studies of the microturbulence is minimal. In the case of lower densities, one would have to assess the issues of drift instabilities in a $\beta>>1$ plasma - an issue that had not yet been studied at any depth.

So far, we have been discussing a situation where the field lines are straight. This is a good approximation in a narrow near-wall region. However, in the bulk plasma one will have to consider the presence of curved magnetic field lines and of (possible) MHD instabilities associated with the curvature of the magnetic field. A concern with regard to these instabilities is that they may set in large-scale convective motions that would cause heat losses at a time scale that is shorter than even the Bohm time scale.

Somewhat paradoxically, the high-beta plasma, whose pressure is almost uniform across the flux surfaces (at least in the hot region where the local beta is very large) is more stable with respect to the curvature-driven modes than its low-beta counterpart. The reason for this is that the magnetic field has too small energy to be able to cause compression or rarefaction of the plasma with $p$=const$>>B^2/2\mu$ (the perturbation of the plasma thermal energy would become prohibitively high). Therefore, only the perturbations with $\nabla\cdot\xi=0$ (with $\xi$ being a standard MHD displacement vector) remain admissible. This imposes an additional constraint on the perturbations allowed to compete in the minimization of the potential energy and thereby improves MHD stability. Possible residual MHD instability is additionally suppressed by a strong *longitudinal* ion viscosity, which is not suppressed by the plasma magnetization. Still, so far there is no proof that there exists closed-field-line configurations stable with respect to all classes of the MHD perturbations. Therefore, considerable efforts in theory and experiment are needed to clarify the situation.

An additional element that may affect the mix of the liner and the hot fusion plasma, is the Rayleigh-Taylor instability of the inner surface of the liner during the deceleration phase near the point of the maximum compression.

Let us first discuss the situation of moderate central betas; in such situations, a magnetic cushion with beta less than one is formed near the walls. For the perturbations with the length-scale smaller than the thickness $\Delta$ of this cushion, the situation will not differ from a so called magnetic Rayleigh-Taylor instability studied in great detail in conjunction with implosions of fast liners. A huge body of theoretical and experimental information is presently available; based on this knowledge, we will certainly be able to evaluate in what parameter domain this instability is not too harmful. Perturbations with the scale-length longer than $\Delta$ are considerably slower and are of less concern.

Consider now the situation where beta is much greater than one until the liner surface (this, as has been pointed out, corresponds to very high central betas). In this case, one has a situation of a heavy liner decelerated by a medium of a very low mass density and essentially isotropic pressure (anisotropy of the magnetic stress tensor is small). This is also a system studied in great detail. Using the available information, we will be able relatively quickly identify an acceptable parameter domain (if existent) for implosions of very high beta loads.

**2. Can Magneto-Inertial Fusion Plasmas Overcome Wall Effects?**

One of the foremost scientific problems in Magneto-Inertial or Magnetic Target Fusion (MTF) is the role of plasma-wall effects on the thermal losses from the plasma core. A general semi-quantitative view of plasma-wall effects and outstanding problems is offered here. There are two fundamental heat loss mechanisms, and they are tightly coupled in the case of high-density MTF compressions. First, there is a steepening of the edge temperature profile by mere contact with the imploding liner, and second there is impurity production caused by bremsstrahlung heating of the liner material and subsequent mixing of vaporized liner material by Rayleigh-Taylor (RT) interchange motions. Beneficial exemplifications of interchange mixing are noted, and may be employed usefully in connection with a scenario for enhancing target gain by refueling the burning MTF plasma [Barnes, 1997].

## (1) Effect of Temperature Gradients near Wall Confined Plasmas

Insight on the effect of temperature profile steepening in the proximity of a wall can be gained from the point of view of a prototypical model of a seminfinite, uniform plasma which is brought into sudden contact with a solid wall [Vekshtein, 1990]. The plasma is hot, high-beta $\beta = \beta_0 >> 1$, and highly magnetized $\omega_{\mathrm{ci}} \tau_{\mathrm{i}} >> 1$, and it is assumed to be supported by the inertia of the wall, so initially $\nabla p = 0$. During readjustment of the plasma profiles on the slow diffusive time scale, quasi-equilibrium $\nabla(p + B^2 / 2) = 0$ is consistently maintained across the plasma.

Thus, as a cool plasma boundary layer advances into the hot interior, it will naturally be accompanied by a density increase and an increased particle accumulation in the layer. Even before the cool layer has reached the interior region, the interior region knows about the cool layer by magnetosonic wave propagation, and thus a slow outward flow of plasma to the wall develops in order to satisfy particle continuity. The hot region effectively loses heat by adiabatic expansion: particles and magnetic flux being carried to the wall at the common $E \times B$ flow speed.

In MTF applications, the wall may act more like an insulator; as, for instance, in the case of a metallic liner undergoing heating to supercritical temperatures without significant ionization, or in the case where the inner surface of the metal liner is coated with a DT fuel layer. In this case the the B-field at the wall remaines constant in time at its initial value, and the outward flow speed scales as $\mathrm{v}_{\mathrm{outflow}} = 0.3(\omega_{\mathrm{ci}}\tau_{\mathrm{i}})^{1/2}\chi_{\mathrm{B}}{}^{1/2}t^{-1/2}$, where $\chi_{\mathrm{B}} = T / eB$ is the Bohm diffusion coefficient. Using some reference parameters for the MTF plasma at the time of peak compression ($t \sim 10\mu s$), the outflow velocity can exceed ~ 1 cm/$\mu$s. This velocity is comparable to currently envisioned liner velocities. This model may suggest that the driver technology may have to be pushed furthur to achieve even higher liner velocities, for otherwise adiabatic heating during liner implosion may be counteracted by wall-induced expansion cooling. Note that this outflow velocity is equivalent to an effective thermal diffusivity in the hot plasma which turns out to be higher than the good classical thermal diffusivity by a large factor, $0.3\omega_{\mathrm{ci}}\tau_{\mathrm{i}}$, i.e. for a high-$\beta$ plasma, the effective thermal conductivity becomes Bohm scaling: $\chi_{\mathrm{eff}} = 0.3\chi_{\mathrm{B}} = 0.3T / eB$.

**-- Caution: Drake et al, may have incorretly used a Bohm coefficient 48 times smaller than the above 0.3 value in their Fusion Technology 1996 paper, Eq (31),. I do not know what coefficient Lindemuth uses in his 1-D simulations. ]**

The energy confinement improves to some extent if the wall acts like a good conductor. Essentially, quasi-equilibrium could then be satisfied at lower flow rates by piling up magnetic field, rather than particles, in the boundary layer. For typical MTF compressed plasmas, the Vekshtein model suggests a well magnetized $\beta \sim 1$ boundary layer will be formed. In this case only a modest increase in the effective thermal diffusivity from the good classical value results, $\chi_{\mathrm{eff}} = \beta_0^{1/4}\chi_{\mathrm{cl}}$. Note that in MTF plasmas the central beta values are typically $\beta_0 \sim 10$.at peak compression.

Although the ideal model has some deficiencies, it reveals how profoundly different the effect of a wall has on heat transport in a high-pressure $\beta >> 1$ wall-supported plasma as compared with its effect on heat transport in the conventional $\beta << 1$ magnetically confined plasma. We will need to generalize this model by including finite plasma volumes with different geometries ( cylindrical, spherical, elliptical, time-dependent compression, and initial low-beta edge regions which exist in many preformed magnetic configurations considered for MTF. We will also need to include wall generated impurity effects in the models, and finally effects due to the specific magnetic topology. For example, in some MTF candidates with topological open field lines on the outer surface, such as the FRC and the spheromak, wall heating by cross-field heat conduction can be limited by rapid parallel heat transport. In particular, most plasma objects formed just before compression are not initially held together by wall inertia, as assumed in the Vekshtein model. Confinement is initially provided by a surrounding magnetic field with equilibruim dictated by $\nabla_{\perp}(p + B^2/2) - B^2\vec{\kappa} = 0$ where $\vec{\kappa}$ is the field line curvature.

Some insight can be gained into how the compression of real objects changes their profiles and gradients and how this relates to the heat transport near the liner. Consider a two-region initial configuration consisting of a medium-pressure core region with modest beta, $\beta = \beta_0$, surrounded by a low-pressure mantle with very low beta $\beta = \beta_1$ , as in the case of an FRC configuration. A self-similar 2D shape-preserving compression is assumed in this exercise. The initial radius of the entire configuration, the initial liner radius, is $r = R_l$, and the initial core-mantle radius is $r = R_\mathrm{b}$. At peak compression, the final liner radius is $r = R_{l*}$, and the final core-mantle radius is $r = R_{\mathrm{b}*}$. We now define a liner compression ratio compression ratio,

$$A = \frac{R_l}{R_{l*}} \tag{1a}$$

and we ask how this is related to the compression ratio of the core region

$$A_\mathrm{b} = \frac{R_\mathrm{b}}{R_{\mathrm{b}*}}. \tag{1b}$$

Intuitively we anticipate that the core will be compressed to a lesser extent, $A_\mathrm{b} < A$. Since the core pressure rises faster than the mantle magnetic pressure a "ballooning" of the core-mantle boundary during the compression is anticipated somewhat analogous to a Vekshtein like flow. To determine the location of the core-mantle radius we assume total pressure balance across the entire configuration (neglecting field line curvature), magnetic flux conservation in each region, and the adiabatic law $p \sim \mathrm{volume}^{-\gamma}$ for each region. The degradation of core compression may be characterized in terms of the parameter $\eta = A_\mathrm{b} / A$, which is given implicitely by

$$A = \left[ \frac{\eta^{(4-3\gamma)}\left(\kappa/\beta_0 - \; (1-f_0^2)^2(\eta^2 - f_0^2)^{-2}/\beta_1\right)}{\left(\dfrac{1-f_0^3}{\eta^3 - f_0^3}\right)^{\gamma} - \kappa} \right]^{\frac{1}{3\gamma-4}} \tag{2}$$

in which $\kappa = p_0 / p_1 = (1+\beta_1^{-1})/(1+\beta_0^{-1})$.is the initial pressure ratio, and $f_0 \equiv R_\mathrm{b} / R_l$. Note that as $A$ approaches $\infty$, $\eta$ asymptotes to a minimum

$$\eta_{\min} = \left(\kappa^{-1/\gamma}(1-f_0^3) + f_0^3\right)^{1/3} \tag{3}$$

Take for example the numbers: $\beta_0 = 0.75, \beta_1 = 0.01$, and $\kappa = 43.29$. Choosing $f_0 =$ separatrix radius/wall radius = 0.4, we first obtain the lower limit $\eta_{\min} = 0.5447$. To reach core fusion temperatures ~ 10 keV, the typical core compression ratio needs to be $A_b = 10$. From Eq. (2), the liner compression ratio turns out to be $A = 13.44$, and the parameter $\eta = 0.748$. The final core beta is increased by a factor of ten $\beta_{0*} = 7.5$, and the beta in the mantle is increased to 0.115. Note that the fractional width of the mantle region has shrunken from an initial value of $1 - f_0 = 0.6$ down to a final value of $1 - f_0 / \eta = 0.465$.

The ballooning of the core plasma and the enhanced steepening of the pressure and temperature profiles caused by compression may excite resistivity-gradient driven turbulence, and enhance heat conduction losses ( see part 3). Because of the high-beta property of compressed MTF objects, it is hoped that ideal ballooning modes may be in the "second stable" regime due to the magnetic well effect. However, at high beta another issue may be with the kinetic ballooning modes, which have a resonance at a frequency near the velocity dependent ion magnetic drift frequency. Because the resonance effect is enhanced by the finite ion-temperature-gradient $\eta_i$ parameter [Hirose, 1996], MTF plasma profiles with steep temperature and density gradients of opposite sign may be particularly susceptible to these kinetic ITG modes. Typical growths rate times are ~ 0.1 Alfven times, and are thus comparable to the microsecond dwell times in MTF.

**(2) Impurities**

The ingestion of impuries from the wall into the plasma is profoundly altered in high pressure, $\beta >> 1$ MTF plasmas. In low-beta tenuous plasma, the impurities emitted from the wall can freely cross the plasma boundary and bury a distance into the plasma determined only by their mean free path against ionization by the plasma electrons. In the case of MTF plasmas, the wall is intensely heated, but it may not freely vaporize and release impurities into the plasma, if the plasma pressure over the wall exceeds the vapor pressure at each moment during the compression. Of course, if the wall temperature reaches the critical temperature the wall material can penetrate the plasma by a mixing process initiated by the RT instability, which develops near the approach to final compression and the ensuing dwell period. On the other hand the RT mixing process will be influence by the outward flow of magnetic flux as we discussed, and this may limit the inward migration of the impurities. The nonlinear development of the RT mixing process with self consistent radiation cooling dynamics will be investigated with comprehensive analytical/numerical tools. Benchmarking of our models with experimental tests of interior cooling rates as inferred by liner compression speeds and spectroscopic measurements will be necessary to sort out the dominant physical processes.

On the reverse side, the RT impurity mixing process may be exploited to our advantage to "refuel" the MTF plasma during the burn phase. If the interior liner surface were coated with a cryogenic DT layer, automatic mixing of cold fuel with the buring DT core during the RT unstable dwell period may prolong the duration of the burn and increase the target gain. This concept will be considered as part of our study on wall-plasma interactions.

Let us now consider liner heating in the case where the open-field-line sheath provides good thermal insulation. Neglecting ohmic heating, the dominant liner heating mechanism then becomes bremmstrahlung radiation. Even with some cross-field heat conduction to the surface the penetration of heat into the interior is much less efficient than radiation since the thermal diffusion distance into the liner $\sqrt{\chi t}$ is usually quite small compared with the mean photon penetration depth from bremsstrahlung. Furthermore, any ablation layer formed by surface conduction heating will not expand away, as we will show. Liner heating during implosion is best described by combining an entropy equation of the form

$$\frac{Ds}{Dt} = \frac{-\nabla \cdot \vec{q}}{\rho T}, \tag{4}$$

with the equation-of-state linking the temperature, $T$, and the density $\rho$ with the pressure $p$ and specific entropy $s$

$$T = T(p,s),\ \rho = \rho(p,s,) \tag{5}$$

To simplify the problem, we will assume that the liner stays thin compared to the radius of its inner surface, $R_l(t)$, so that the attenuation of bremsstrahlung heat flux with distance $x = r - R_l(t)$ into the liner material will be $q \approx q_0 \exp(-x/\lambda)$, where the photon absorption mean free path is $\lambda = \lambda_c \rho_c / \rho$, and the "c" subscript refers to the properties of the condensed phase at $t = 0$. By taking into account cylindrical convergence, the rate of entropy change for a Lagrangian fluid element $dx_0 = \rho R_l(t) dx / \rho_c R_l(0)$ which is initially at depth $x_0$ is given by

$$\frac{\partial s(x_0,t)}{\partial t} = \frac{q_0}{T(x_0,t)\rho_c \lambda_c} \exp\left[-\frac{x_0}{\lambda_c}\frac{R_l(0)}{R_l(t)}\right] \tag{6}$$

Note that thickening of the liner by cylindrical convergence increases the photon attenuation, as manifest by the instantaneous compression ratio $R_l(0)/R_l(t)$ appearing in Eq. (6). The pressure distribution within the liner material is given by

$$p_l(x_0,t) = p_{\text{sur}} + \rho_c g x_0 R_l(0) / R_l(t) \tag{7}$$

where the total plasma pressure, kinetic plus magnetic, exerted on the inner surface is $p_{\text{sur}} = p(1+\beta^{-1}) \approx p$, and $g$ is the instantaneous liner acceleration ( $g > 0$ for inward liner acceleration during the run-in phase, and $g < 0$ for inward liner deceleration during the dwell period).

For simplicity let us neglect the change in the liner density during implosion. This may not be a bad assumption even at high temperatures because the liner is also subjected to high pressures. Then $Tds = C_v dT$, and Eq (6) describes the temperature evolution for each Lagrangian fluid element,

$$\rho_c C_v \frac{\partial T(x_0,t)}{\partial t} = \frac{q_0}{\lambda_c} \exp\left[ -\frac{x_0}{\lambda_c} \frac{R_l(0)}{R_l(t)} \right] \tag{8}$$

If we next assume uniform plasma profiles, then the bremmstrahlung radiation power emitted per unit volume of a hydrogenic plasma is given by [Glasstone and Lovberg, 1960]

$$P_{\mathrm{brem}} = 1.69 \times 10^{-26} n^2 \theta^{1/2} \quad \text{Watts / m}^3 \tag{9}$$

where $n(\mathrm{cm}^{-3}), \theta(eV)$, are the plasma electron density and temperature, respectively. In a self-similar compression, the axial compression factor and the radial compression factor, $A(t) = R(0)/R(t)$, are the same, and for an adiabatic ideal gas $\gamma = 5/3$, so that $n = n(0)A^3$, and $\theta = \theta(0)A^2$. Utilizing these relations, Eq.(9) becomes

$$P_{\mathrm{brem}} = 1.69 \times 10^{-26} n(0)^2 \theta(0)^{1/2} A(t)^7 \quad \text{Watts / m}^3 \tag{10}$$

Since the plasma is optically thin to its own bremsstrahlung radiation, the heat flux falling on the inner liner surface is simply

$$q_0 = \alpha R_l(t) P_{\mathrm{Brem}} \quad \text{Watts / m}^2 \tag{11}$$

where the shape coefficient $\alpha$= (volume of the plasma) /( $R_l(t) \times$liner surface area) remains constant for a self-similar compression. Utilizing Kramers' photoionization formula, [Zel'dovich and Raizer, 1966], the photon mean free path in the liner material scales with the cube of the photon energy. Thus we can write for almost all candidate liner materials

$$\lambda_c = \lambda_{c10} \left( \frac{\theta(keV)}{10} \right)^3 = \lambda_{c10} \left( \frac{\theta(0)(eV)}{10^4} \right)^3 A(t)^6 \tag{12}$$

where $\lambda_{c10}$ (m) is the average mean free path of photons coming from a 10 keV plasma. By combining Eqs.(8-11), we obtain finally

$$\frac{\partial T(x_0,t)}{\partial t} = 1.69 \times 10^{-14} \left( \frac{\alpha}{\rho_c C_v \lambda_{c10}} \right) R(0) n(0)^2 \theta(0)^{-5/2} \exp\left[ -\frac{x_0}{\lambda_c} A(t) \right] \tag{13}$$

Apart from the liner thickening effect, the compression factor drops out.

To minimize liner heating, an important consideration in the choice of liner materials is the $\sim Z^3$ dependence in the photon absorption crossection $\mu = 1/\rho_c \lambda_c$, for $Z < 30$ [LLNL, 1969] which favors low-$Z$ materials. Let us then take, for example, a lithium liner with material properties $\rho_c C_v = 2.1\times10^6$ J/m$^3$/K, and $\lambda_{c10} = 0.08$ m. For nominal initial plasma conditions:

$R(0) = 0.1\,\text{m}$, $\theta(0) = 100\,\text{eV}$, $p(0) = 2n(0)\theta(0) = 6.4\,\text{MP}$, $\alpha = 0.4$,

the rate of temperature change at the inner liner surface ($x_0 = 0$) is $1.78\times10^9\,\text{K/s}$. If the compression time is $\sim 5\mu s$, the final liner temperature will be 8000 K which is well above critical temperature for lithium, $T_{\text{crit}} = 3223\,\text{K}$. Nevertheless, the liner pressure at the surface $p_l(0,t) = p_{\text{sur}} \approx p \approx p(0)A(t)^5$ , appears to remain well above the vapor pressure of the lithium $p_{\text{vap}} = 8.5\times10^4 \exp(-2.17\times10^4 / T)$ MPa. This means that impurity blowoff from the surface and volume vaporization ( growth of vapor bubbles and disruption of the fluid ) can be avoided, and therefore liner impurity atoms cannot be brought into the plasma by liner heating alone.

It thus appears that the liner fluid can remain intact until the onset of the dwell period, $g < 0$ , when the RT instability and subsequent interchange mixing of the supercritical fluid with the core plasma can begin. The question of what fraction of liner material will undergo mixing depends on many details of the RT instability which need analytical and numerical formulation. Possible mitigating effects, such as line-tying on open field lines [Prater 74], the effect of a non-steady $g$ -force [Hattori 1986] and the fact that the pressure inside the liner falls off with depth, so that the liner density may also do the same, need to be taken into account. However it is clear that the depth of the heated layer as suggested by Eq. (13) will determine the maximim amount of impurity pollution.

Although the temperature of a lithium liner can approach 1 eV, it is still virtually unionized because of the very high liner pressures at peak compression, $p_l \sim 10^6\,\text{MP}$. Since for all metals the supercritical fluid state is highly resistive, the liner may thus lose its good flux conserving property during the late phase of the compression. The resulting dissipation of magnetic flux near the wall would of course be compensated by an outward flow of flux from the plasma core to the wall. Such a Vekshtein-like flow could potentially degrade energy confinement.

In summary, the changing thermodynamic and fluid dynamic properties of the liner during compression and its significance on thermal losses from the plasma seem to be critical MTF issues. Analytical models will developed and incorporated in the numerical simulations in order to carry out systematic plasma-wall interaction studies.

**(3) Thermally Driven Convection Cells**

It is well known in tokamak plasmas that the plasma boundary has a high level of fluctuations. Some of the model candidate for edge turbulence are resistivity gradient driven turbulence and involve centering of the current density fluctuations about the mode rational surface $k \cdot B = 0$ , while the perturbed motions are growing on only on side of the surface. The essential features of the nonliner turbulent state involve a balance between the resistivity gradient drive and the parallel thermal conduction damping. When impurities are present there is a new drive term, namely the well-known thermal or "condensation" instability which results in the low temperature edge where the impurity line radiation rate increases as the temperature goes down. The thermal drive can couple with the resistivity gradient drive to enhance thermally driven convective cell turbulence. The coupling comes about because the perturbed potential appearing in Ohm's law due to the cross-field resistivity gradient also enters the temperature equation as a convective $\tilde{E}\times B$ perturbed flow. As shown by Thayer et al [Thayer 1987], the linear growth rates scales with impurity density, and non-linear diffusion coefficients are proportional to the impurity density squared. Hence, these modes may be particurily worrisome in the very high-density wall confined MTF plasmas. Because MTF wall-plasma effects occur in an accelerated reference frame, the linear analysis of thermally driven convection cells would need to be modified by including an effective time-varying $g$ drive in the vorticity (momentum) equation. In addition, the previous analysis were based on an electrostatic approximation, with constant pressure nT assumed. As we have seen, however, even in the peripheral region of MTF plasmas, the plasma beta is not negligible, so in fact the stability analysis would have to be modified to include magnetic perturbations.

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## APPENDIX D: PROPOSING TEAM BIOGRAPHIES

**Roger J. Bartlett**
**Los Alamos National Laboratory**

Roger Bartlett joined Los Alamos Scientific Laboratory in 1972 and is now a team leader in the Hydrodynamics and X-ray Physics Group, P-22. He received a BS and MS in Electrical Engineering and a Ph.D. in Physics from Iowa State University. A merit scholarship and a NFS fellowship supported his studies. While at Los Alamos he was the technical project leader for LANL's synchrotron radiation project at the National Synchrotron Light Source at Brookhaven National Laboratory and was the PI for five consecutive three year LDRD (Laboratory Directed Research and Development) projects in solid state and atomic physics. A common theme in his research has been the use of synchrotron radiation to probe the atomic and solid state properties of matter. He was one of the early users of synchrotron radiation as a tool for research having performed his first experiments on the Tantalus I storage ring (University of Wisconsin) in 1968. He has authored or co-authored over ninety refereed publications in these fields.

**James H. Degnan**
**Air Force Weapons Laboratory**

Dr. James H. Degnan received his PhD in Physics in 1973 from the Dept of Physics and Astronomy, University of Pittsburgh, where he did his thesis work on experimental nuclear reaction studies. This included charged particle, neutron, and gamma spectroscopy of reaction products from 12 to 18 MeV light ion projectiles bombarding medium atomic number target nuclei. He worked at the Air Force Weapons Laboratory (AFWL), later known as the Weapons Laboratory (WL), later incorporated into the Phillips Laboratory (PL), and still later incorporated into the Air Force Research Laboratory, since 1973. There he designed, conducted, and directed research on gas puff and foil plasma implosions, puff gas coaxial plasma guns, inductive store - fuse opening switch and plasma flow switch development and application, subkilovolt X-ray diagnostic development (including fast high current bolometers and spectrum deconvolution codes), automated rezoners for Lagrangian MHD codes, diagnostics of neutron and gamma emission from 200 MeV protons incident on thick targets, explosive magnetic flux compression generators, solid liner implosions (including cylindrical, conical, and quasi-spherical) and applications; compact toroid formation, compression, and acceleration; and compact, portable pulsed power for high impedance loads. He is presently a senior physicist (GS-15 = DR-IV) in the High Power Systems Branch of the Directed Energy Directorate of the Air Force Research Laboratory (AFRL/DEHP).

Some recent, relevant publications include:

(1) "Compact Toroid Formation Experiments at the Weapons Laboratory", J.H.Degnan et al, in ISPP-8 "Piero Caldirola", Physics of Alternative Magnetic Confinement Schemes, eds. S.Ortolani and E.Sindoni, Societa Italiana di Fisica, Bologna, Italy, 1991 (*invited paper*)

(2) "Compact Toroid formation, compression, and acceleration", J.H.Degnan et al, Phys.Fluids B5, 2938 (1993)

(3) "Electromagnetic implosion of a spherical liner", J.H.Degnan, et al, Phys.Rev.L.74, 98 (1995)

(4) "Compression of compact toroids in conical-coaxial geometry", J.H.Degnan, et al, Fusion Technology 27, 107 (1995)

(5) "Multimegajoule electromagnetic implosion of shaped solid-density liners", J.H.Degnan, et al, Fusion Technology 27, 115 (1995)

(6) "Solid quasi-spherical shell liner implosions used to compress hot hydrogen working fluid", J.H.Degnan et al, presented at Megagauss-7 Conference, Sarov, Russia, Aug 96 (to be in Megagauss-7 Proceedings)

(7) "Formation, Compression, and Acceleration of Magnetized Plasmas", J.H.Degnan et al, in Current Trends in Fusion Research, Ed. E.Panarella, Plenum Press, p.179-195, 1997

**Carl Ekdahl**
**Los Alamos National Laboratory**

Carl Ekdahl earned his Ph. D. in Physics at the University of California, San Diego, in 1971. He spent two years as a Research Physicist at Scripps Institute of Oceanography measuring and interpreting the increase in atmospheric carbon dioxide resulting from mankind's use of fossil fuels. After spending the next two years at the Laboratory of Plasma Physics at Cornell University directing experiments to demonstrate heating of plasmas with intense relativistic electron beams, he joined Los Alamos National Laboratory in 1975 to carry out experiments in controlled thermonuclear fusion. In 1980 he left to join Mission Research Corporation in Albuquerque where he led experiments with atmospheric propagation of intense relativistic electron beams. He returned to Los Alamos in 1982 for a short while to lead further experiments to heat high-density plasma with electron beams, and to launch a high-power microwave source development program. In 1983 he joined the Sandia National Laboratories' to continue with beam propagation experiments and was promoted to Supervisor of the High-Energy Beam Physics Division the next year. He finally returned to Los Alamos in 1986 to design, execute, and analyze experiments using the radiation from underground nuclear weapon tests. As leader of a nuclear test diagnostics group he directed their transition into above ground experimental activities, including the first lab-to-lab experiments with VNIIEF. He is presently the program manager for High Energy Density Physics in Nuclear Weapon Technologies.

**John M. Finn**
**Los Alamos National Laboratory**

John Finn obtained his Ph. D. from the University of Maryland in 1974. His dissertation research was in the area of Lie transforms applied to particle motion in the magnetosphere and in mirror machines. This work was the basis for the Lie transform approach to particle dynamics in accelerators, developed into the code MARYLIE by Alex Dragt and co-workers. He did postdoctoral work at the Princeton University Plasma Physics Laboratory from 1974-76, where he worked on resistive instabilities and on destruction of magnetic flux surfaces as a model for tokamak disruptions. With Predhiman Kaw, he discovered and investigated the coalescence instability, which has been found to be a major aspect of nonlinear MHD. He worked during the period 1976-79 at Cornell University on kinetic and MHD instabilities in compact tori with an energetic ion component (ion rings). He and Ravi Sudan wrote a review paper on this subject which was published in *Nuclear Fusion* in 1982. He worked at the Naval Research Laboratory from 1979-82 in the area of compact tori and RFP's; specifically on ballooning and tilting modes in spheromaks and compact tori with an energetic ion component, and on resistive instabilities in RFP's and spheromaks, and their diamagnetic stabilization. He also worked on toroidal equilibria of electron beams in modified betatrons. He worked at the University of Maryland from 1982-93. During this time he worked in spheromak theory, specifically on spheromak formation in the MS device, on magnetic helicity and helicity injection, and on temperature gradient driven semi-collisional tearing modes in spheromaks and RFP's. He worked on convection and flow shear generation at the tokamak edge (H mode studies), discovering the linear instability responsible for generation of shear flow in the presence of convective vortices, and the manner in which this shear flow reduces the turbulence level. At this time he also worked in the magnetohydrodynamics of the solar corona and convection zone, specifically on MHD instabilities in 2D coronal arcades and 3D coronal loops, on the associated magnetic reconnection processes in 3D. He also worked on the fast dynamo problem, in which the flow was taken to have chaotic flow lines. His paper with Ed Ott was the first work to elaborate the relationship between the lagrangian chaotic properties of the flow and the intermittent aspects of the generated magnetic field. He has been at LANL since 1993. At LANL he has worked on linear and nonlinear studies of resistive wall instabilities and locking in tokamak geometry, and the application to tokamak disruptions. He discovered and investigated a new plasma instability driven by shear in the velocity parallel to the magnetic field, and discovered with L. Turner a new streaming instability in nonneutral beams with turning points. He has over 85 publications in refereed journals. In 1987 he was elected fellow of the American Physical Society.

RECENT PUBLICATIONS

1. "Resistive Wall Stabilization of Kink and Tearing Modes,"J. M. Finn, *Phys. Plasmas* **2**, 198 (1995).
2. "Streaming Instabilities of a Nonneutral Plasma with Turning Points," L. Turner and J. M. Finn, *Phys. Plasmas* **2**, 1378 (1995)..
3. ″Stabilization of Ideal Plasma Resistive Wall Modes in Cylindrical Geometry: The Effect of Resistive Layers,″ J. M. Finn, *Phys. Plasmas* **2**, 3782 (1995).
4. "New Parallel Velocity Shear Instability", J. M. Finn, *Phys. Plasmas* **2,** 4400 (1995).
5. "Parallel Transport in Ideal Magnetohydrodynamics and Applications to Resistive Wall Modes", J. M. Finn and R. A. Gerwin, *Phys. Plasmas* **3**, 2469 (1996).
6. "Mode Coupling Effects on Resistive Wall Instabilities", J. M. Finn and R. A. Gerwin, *Phys. Plasmas* **3**, 2344 (1996).
7. "Time-Dependent Perturbation Theory for the Construction of Invariants of Hamiltonian Systems", H. R. Lewis, J. W. Bates, and J. M. Finn, *Physics Letters A* **215**, 160 (1996).
8. "Magnetic Reconnection and the Topology of Interacting Flux Tubes", Y.-T. Lau and J. M. Finn, *Phys. Plasmas* **3**, 3983 (1996).
9. "Orbital Resonances and Chaos in a Combined RF Trap", J. M. Finn, R. Nebel, A. Glasser, and H. R. Lewis, to appear in *Phys. Plasmas* (1997).

**Richard Gerwin**
**Los Alamos National Laboratory**

Dr. Richard Gerwin was awarded the D.Sc. degree with distinction in 1966, at the Technical University at Eindhoven, the Netherlands. His thesis was developed jointly under the auspices of this University and the Dutch government's Instituut voor Plasmafysica. It dealt with inertial effects in the diffusion of a plasma across a magnetic field, including the effects of rf fields. He worked in plasma physics at the Boeing Scientific Research Laboratories from 1959 to 1971, except for a two-year leave of absence for his thesis research in the Netherlands. He then worked at Los Alamos National Laboratory, beginning in 1971 until his retirement in 1995. Since his retirement, he has consulted at the Laboratory on plasma accelerators and on liner compression of fusion plasmas. He lead the Plasma Theory Group in alternate concepts research at Los Alamos, in the Controlled Thermonuclear Research Division (CTR), from 1979 through 1989; and Dr. Gerwin was elected a Fellow of the Amerian Physical Society in 1983. In 1979, he published a paper in *Nuclear Fusion*, with R. C. Malone, on compression of plasmas by compressible liners. Dr. Gerwin continues to consult at the Laboratory, and is also an adjunct professor of Nuclear Engineering at North Carolina State University, Raleigh, North Carolina.

**Lawrence Green**
**Program Manager, Fusion Programs**
**Westinghouse Science and Technology Center**

Dr. Green has has over ten years of fusion technology experience, including 6 years in the study of blanket design and shielding for fusion reactors. He also has over 20 years of experience in the area of fission reactor design, development, and safety. He is currently serving as Fusion Program Manager in the Energy Systems Engineering Department at the Westinghouse Science and Technology Center, where he is responsible for program development and engineering activities for all fusion-related activities. Current programs include the International Fusion Materials Irradiation Facility (IFMIF), ITER First Wall/Blanket/Shield, Plasma Facing Components, ITER Engineering Design Program, and ELISE Heavy Ion Beam Fusion Program.

As a Visiting Scientist at the Swiss Federal Institute of Technology (EPFL), Dr. Green was the Lead Experimental Scientist at the LOTUS facility, Lausanne, Switzerland, in a joint program involving Westinghouse, DOE and EPFL. This facility is dedicated to the experimental and theoretical study of fusion blankets and shielding. Dr. Green performed radiation transport studies and blanket and shield design at the Westinghouse Fusion Power Systems Department for magnetic and inertial confinement fusion systems. He participated in fusion reactor plant systems studies and conducted feasibility and design studies on the use of integral blanket neutronics experiments for data and code verification.

As a Visiting Professor in the Nuclear Engineering Dept., Ben Gurion University, Beer Sheva, Israel, Dr. Green performed studies on tight lattice, high-conversion water reactors and associated fuel cycles.

Dr. Green has authored or co-authored approximately 70 papers in fission and fusion-related technology.

**James H. Hammer**
**Lawrence Livermore National Laboratory**

James H. Hammer received his B.S.(Physics) from Arizona State University in1973 and his Ph.D.(Physics) at University of California-Berkeley in 1978. Began employment at Lawrence Livermore National Laboratory, 1979, Magnetic Fusion Energy, Theoretical Computations Group. Work has included examinations of various theoretical issues related to the Beta II compact torus (CT) experiment, a plasma model of the gun helicity injection and many studies (both numerical and analytical) of magnetohydrodynamic equilibrium and stability of several configurations. Served as program leader for compact torus acceleration experiment 1991-1994. Has made significant contributions to the invention and development of the CT accelerator, CT fueling and current drive for tokamaks, the CT pulsed x-ray source and the Fast Ignitor ICF concept. Holds a patent for a method of tapping electrical energy from the solar wind for space power and propulsion. Currently involved in radiation-magnetohydrodynamic modeling of dense, magnetized plasmas such as radiating z-pinches and laser-produced plasmas.

**HONORS:**

Roy Lester Frank Memorial Award, 1978.

**Ronald C. Kirkpatrick**
**Los Alamos National Laboratory**

Dr. Kirkpatrick is currently a Non-proliferation and International Security Division staff member. He has degrees in Electrical Engineering (BS, 1959) and Physics (MS, 1963) from Texas A & M University and in Astronomy (NASA Traineeship, PhD, 1969) from the University of Texas. He has worked at Gulf States Utilities (Port Arthur, TX), NASA Ames Research Center (Mountain Veiw, CA), Southwest Research Institute (San Antonio, TX), Applied Research Lab (Austin, TX), and NASA Goddard Space Flight Center (NRC postdoc, Greenbelt, MD). He taught Physics and Astronomy at Texas A & M University (1971-1972) before coming to Los Alamos in 1973.

At Los Alamos Dr. Kirkpatrick previously worked in the Thermonuclear Applications Group for 15 years and in the old Plasma Theory and Laser Fusion Group for 5 years. His chief expertise is in the areas of computational atomic physics, extreme non-LTE processes in astrophysical plasmas, fusion ignition physics, charged particle transport, and radiation transport. He originated the concept of an ignition critical profile, and long with Irv Lindemuth, he has advocated magnetized target fusion (MTF) for over a decade. From 1994 into 1995 he was the principle investigator for a Laboratory Directed Research and Development project for MTF theory and computation, and he participated in the first collaborative MTF related experiment (MAGO) with the Russian counterpart of Los Alamos. Dr. Kirkpatrick has numerous publications in the areas of atomic physics, astrophysics, and fusion physics, a few of which have numerous citations.

**Gerald F. Kiuttu**
**Air Force Research Laboratory**

Dr. Gerald F. Kiuttu received his BSE (Magna Cum Laude) in Engineering Science at Arizona State University in 1975. He received his MS in 1980 and his Ph.D. in 1986 in Nuclear Engineering (Plasma Physics) at the University of New Mexico. He worked at the Air Force Weapons Laboratory from 1975 to 1980 as a military officer, primarily on terawatt range soft X-ray and vacuum ultraviolet diagnostics. He was a research assistant in the Dept of Chemical and Nuclear Engineering at the University of New Mexico in 1980 to 1982, where his work included spatially resolved soft X-ray spectroscopy. As Senior Scientist at Mission Research Corp. in Albuquerque from 1982 to 1991 he worked on a variety of pulsed power innovations, applications and related diagnostics, including charged particle beams, high power microwaves, pulsed transformers, cloth fiber cathodes, hollow Z-pinches, plasma jet diagnostics, and more. Since 1991 he has been at the Air Force Research Laboratory (formerly Phillips Laboratory), where he is Pulsed Power Team Leader for the High Power Systems Branch. Here he has conducted and led research on compact toroids and explosive pulsed power systems. Compact toroid work included their use as fast switches and initiators of plasma focus-like discharges. He has worked on plasma injection, explosive flux compression generator design and modeling, and has fielded pulsed power diagnostics on large Russian explosive generators. He is co-inventor for U.S. Patent No 4918325, "Fast Risetime Pulse Power System," April 17, 1990 (AF Invention No 17,793). He is a member of the American Physical Society, the Institute of Electrical and Electronic Engineers, and the Sigma Xi Scientific Research Society.

**Irvin R. (Irv) Lindemuth**
**Los Alamos National Laboratory**

Dr. Lindemuth is currently Project Leader for International Collaboration in the High Energy Density Physics Program at the Los Alamos National Laboratory, where his primary responsibility is to provide technical leadership for an historic scientific collaboration between Los Alamos and Los Alamos' Russian counterpart, the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) at Sarov (Arzamas-16). Prior to joining Los Alamos in 1978, he was a technical staff member in A-Division at the Lawrence Livermore National Laboratory where he was involved in fusion research. Dr. Lindemuth received his B.S. degree in Electrical Engineering from Lehigh University in 1965 and his M.S. and Ph.D. degrees in Engineering--Applied Science from the University of California, Davis/Livermore in 1967 and 1971, respectively. His areas of expertise include thermonuclear fusion and advanced numerical methods for the computer simulation of fusion plasmas and related pulsed power technology. He has published numerous papers in refereed journals and proceedings of major international conferences. He has been involved in a wide range of fusion and high energy density physics programs spanning essentially all of the ten orders of magnitude in density and time space from magnetic fusion energy plasmas to inertial confinement fusion plasmas. An internationally recognized pioneer in the application of implicit, non-split computational methods to magnetohydrodynamics, he has achieved widespread recognition for his large-scale numerical simulations of a variety of fusion and other high-density plasma systems. In addition to his accomplishments in modeling high temperature plasmas, he has formulated a variety of novel pulsed power computer codes that have led to important advances in laboratory programs. His codes have stimulated the development of several types of fast opening switches, and he has designed opening switch experiments, which set US records for transfer of explosively generated electrical energy. He is a US pioneer on magnetized target fusion (MTF) and performed the first comprehensive survey of the parameter space in which MTF was likely to work. Even before the collapse of the Soviet Union, he recognized that the Soviets had developed advanced technology in the areas of ultrahigh magnetic fields and ultrahigh energy electrical pulse generation which significantly exceeded US capabilities and which were motivated by the Soviet MTF program known as MAGO. Dr. Lindemuth played an essential role in establishing the collaboration with VNIIEF, which provides US access to Russian advances in MTF and pulsed power technology. In 1992, he was the recipient of a Los Alamos Distinguished Performance Award for his work in the formative stages of the LANL/VNIIEF collaboration. His relationship with Russian scientists will ensure that the US takes full advantage of Russian advances relevant to MTF and his computational expertise will ensure that the US MTF program has a strong synergism between experiment, theory, and detailed, multidimensional computational modeling.

**Richard D. Milroy**
**Redmond Plasma Physics Laboratory**
**University of Washington**

Since January of this year, Dr. Milroy is a "Principal Research Scientist" at the University of Washington's Redmond Plasma Physics laboratory. He is primarily responsible for developing and applying numerical models in support of the experimental fusion related plasma physics research program at this laboratory.

From December of 1992 through December of 1997, Dr. Milroy was "Director of Software Development" at MCM Enterprise Ltd., in Bellevue WA. During that time he led a small team to develop commercial software to analyze data from hydroelectric generator instrumentation. This work included the recent development of a complete data acquisition and analysis package using an Expert System for data interpretation and analysis. He was also responsible for the development of Allen-Bradley's MessageBuilder software product. This commercial product is used to configure a line of Allen-Bradley's industrial control display terminals.

Prior to that Dr. Milroy spent 15 years (1978-1992) at STI Optronics in Bellevue WA., where he became a nationally recognized expert in the field of computational plasma physics. He has worked extensively in the areas of Field Reversed Configuration (FRC) formation, stability, and transport. This work has involved the development of and application of several numerical models including dynamic two and three-dimensional MHD computer codes to study the formation and stability of FRCs. In addition, he has developed numerical models in support of other areas of research at STI. These include the energy exchanger FLOW code to evaluate the parametric performance of the STI energy exchanger, a hydrodyanamic model of laser flow loops, a Monte-Carlo simulation of high energy (relativistic) electrons with a gas in an arbitrary electro-magnetic field, and a integrated model including hydrodynamics, discharge physics and gas kinetics for simulating high power transverse flow $CO_2$ lasers.

Dr. Milroy has authored or co-authored over twenty refereed publications.

**Ralph W. Moir**
**Lawrence Livermore National Laboratory**

**Education**

B.S. 1962--Engineering Physics, University of California, Berkeley

Sc.D. 1967--Nuclear Engineering, MIT, Cambridge, Mass.

**Professional Associations, Societies and Honors**

Registered Professional Nuclear Engineer in the State of California, Registration number NU782.

American Physical Society, Fellow 1981, Plasma Physics Division

American Nuclear Society, Fellow 1989, Fusion Energy Division,

American Association for the Advancement of Science

**Publications**

1. R. W. Moir and R. F. Post, "Yin-Yang Minimum--B Magnetic Field Coil", *Nuclear Fusion*, 9, 253 (1969).
2. R. W. Moir and W. L. Barr, "Venetian-Blind Direct Energy Converter for Fusion Reactors", *Nuclear Fusion*, 13, 35-45 (1973).
3. R. W. Moir, "The Fusion-Fission Fuel Factory, Chapter 15, p. 411-451, in *Fusion*, Vol. 1 Part B, edited by E. Teller, Academic Press, New York (1981).
4. R. W. Moir, et al., "Study of a Magnetic Fusion Production Reactor", A series of eight articles on tritium production. *J. Fusion Energy*, 5, 255-331 (1986) and 6, 3-88 (1987).
5. R. W. Moir, "Pacer Revisited", *Fusion Technology* 15 1114 (1989).
6. B. G. Logan, R. W. Moir, M. Tabak, R. L. Bieri, J. H. Hammer, C. W. Hartman, M. A. Hoffman, R. L. Leber, R. W. Petzoldt, M. T. Tobin, "Compact Torus Driven Inertial Confinement Fusion Power Plant HYLIFE-CT," UCRL-ID-106403 (1991). SRD
7. A. Szoke and R. W. Moir, "A Practical Route to Fusion Power," *Technology Review*, 94 p 20- 27 (July 1991).

8. R. W. Moir et al., "Inertial Fusion Energy Power Plant Design Using the Compact Torus Accelerator: HYLIFE-CT ," *Fusion Technology* 21 1492 (1992).
9. R. W. Moir, R. L. Bieri, X. M. Chen, T. J. Dolan, M. A. Hoffman, P. A. House, R. L. Leber, J. D. Lee, Y. T. Lee, J. C. Liu, G. R. Longhurst, W. R. Meier, P. F. Peterson, R. W. Petzoldt, V. E. Schrock, M. T. Tobin, W. H. Williams, "HYLIFE-II: A Molten Salt Inertial Fusion Energy Power Plant Design-Final Report," *Fusion Technology* 25 (1994) 5-25.
10. S. Sahin, R. W. Moir, and S. Unalan, “Neutronic Investigation of a Power Plant Using Peaceful Nuclear Explosives,”*Fusion Technology* 26 (1994) 1311-1325.
11. R. W. Moir, “Liquid First Walls for Magnetic Fusion Energy Configurations,” *Nuclear Fusion* 37 (1997) 557-566.

**Ronald W. Moses, Jr.**
**Los Alamos National Laboratory**

Ron Moses is a Technical Staff Member in the Fluid Dynamics Group (T-3) at Los Alamos National Laboratory. Dr. Moses received his Ph.D. in Physics from the University of Wisconsin, Madison in 1968, specializing in the physics of electron imaging. After leaving Wisconsin, he was an NSF Postdoctoral Fellow for one year at the Cavendish Laboratory, Cambridge University, England. Over the next several years he held research and teaching positions in the Institut fur theoretische Physik of the Technische Hochschule Darmstadt, Germany; the University of Chicago; and the University of Wisconsin, Madison. Ron joined Controlled Thermonuclear Research Division (CTR) at Los Alamos National Laboratory in 1976. He is an author of over 100 scientific papers and reports in the subject areas of plasma physics, particle optics, wave optics, accelerator physics, and superconducting energy storage. While in CTR Division, Ron was the co-originator of the kinetic dynamo theory of Reversed-Field Pinch sustainment. He was also leader of a three person research team in the explanation of a collisionless magnetic reconnection and plasma heating mechanism. From 1990 to the present Ron has worked in the fields of pulsed power, magnetized target fusion (MTF), ground penetrating radar, atmospheric infrasound, and fluid turbulence. Ron has had a long-standing interest in MTF; he led the effort referenced as: R. W. Moses, R. A. Krakowski and R. L. Miller, "A Conceptual Design of the Fast-Liner Reactor (FLR) for Fusion Power," (February, 1979) LA-7686-MS. This year-long MTF project addressed issues ranging from basic plasma physics to the engineering of blast containment. Ron has contributed to the plasma physics and systems modeling of LANL’s recent efforts in MTF. He brings to this project a broad range of experience in physics and engineering as well as expertise in MTF.

**Dr. Paul B. Parks**
**General Atomics**

Dr. Parks is a plasma physicist, with a strong and diversified interdisciplinary background in classical physics and applied science. He has extensive experience in a number of diverse theoretical and applied areas connected with magnetic and inertial fusion research. He has published 57 papers in the refereed Physical Journals and published a book on pellet ablation in plasmas. Highlights of his scientific accomplishments and creativity are given below in chronological order:

Dr. Parks is especially recognized for his pioneering work on pellet/plasma interaction theory, and predictions of his widely accepted pellet ablation model agree well with measured pellet ablation rates in tokamak plasmas.

He developed a novel plasma impurity control concept using radio frequency waves as a momentum source.

Dr. Parks performed fast wave ICRH antenna coupling calculations and developed the theory of Faraday shields for application to cavity launchers. He holds (with others) a U. S. Patent for a novel ICRH cavity launcher, which was built and installed on the DIII-D tokamak.

Dr. Parks made a theory of current drive in tokamak plasmas which involved combining ECRH with an induced local gradient in the toroidal magnetic field.

For five years, Dr. Parks provided theoretical support for the GA/Nagoya mirror fusion program involving the RFC-XX double cusp device, and interacted with LLNL on related mirror problems. His most notable contribution was introducing an innovative method of stabilizing mirror plasmas using radio-frequency pondermotive forces. The method was successfully confirmed by experiments on the Phaedrus device at U. of Wisconsin.

He has conducted SDI related research in several applied areas involving high-power microwave generation, MHD and gas-dynamic phenomena in electromagnetic railgun launchers, exploding foil fuses, hypersonic plasma wind tunnels, and other related devices. He developed a theoretical model of a variable cross section axial-flow Z-pinch for hyper velocity projectile acceleration.

With Dr. R. Fisher , he started a DOE-funded program in collaboration with PPPL using high-speed low-Z refractory pellets as a plasma diagnostic tool for measuring the distribution function of confined alpha particles During the past seven years he was in charge of the modeling effort for the Pellet Charge Exchange Diagnostic project, which recently led to the first measurements of fusion born fast alpha particles inside the Princeton TFTR tokamak.

During the spring of 1991 and summer of 1995 he was a visiting scientist at the Max-Planck Institute for Plasma Physics, Garching, Germany, where he worked on several pellet ablation problems and divertor surface ablation by high-heat fluxes induced during plasma disruptions. One outstanding issue was the source of pellet ablation oscillations. He developed a theory explaining the oscillations which invoked E_B rotation drive as the cause of a magnetized Rayleigh-Taylor instability.

Currently Dr. Parks has received funding from ITER to work on a new concept proposed by M. Rosenbluth involving the injection of cryogenic liquid jets in the plasma to mitigate plasma disruptions. Models for penetration, jet breakup time, and stability, are being developed in collaboration with ITER. He is also leading the effort for a proof-of-principle experiment on DIII-D.

**Robert E. Reinovsky**
**Los Alamos National Laboratory**

Robert E. Reinovsky received his ME degree in 1971 and his PhD in 1973 from Rensselaer Polytechnic Institute in the Electrophysics Department. From 1974-1986 he worked at the AF Weapons Laboratory (now the AF Phillips Laboratory) in plasma and pulse power physics, where his principle interests were high density plasma implosions, radiation processes, plasma diagnostics and pulse power physics. He was responsible for a developing and building four generations of the world-class SHIVA family of high current, low impedence pulse power systems. Techniques in ultra high current, high explosive pulse power that had develped in Los Alamos starting in the 1950's caught his imagination. He joined Los Alamos National Laboratory in 1986 to continue work applying these techniques to ultra-high current plasma systems for applications to High Energy Density Physics. He led the explosive pulse group from 1990 to 1993 and then joined the HEDP program as project leader for! the Athena pulse power project and then as Project Leader/Chief Scientist for the HEDP program.

**Edward L. Ruden**
**Air Force Research Laboratory**

Dr. Edward L. Ruden, Ph.D. Physics, UC Irvine, 1988. Since Dr. Ruden received his degree, he has performed research in the area of high energy density states of matter for the Air Force Research Laboratory's High Power Systems Branch and its predecessors. He has developed several interferometric systems for the diagnosis of plasmas using coherent radiation sources across a broad spectrum: millimeter wave, far IR, visible, and UV. His latest effort in this area has been to push the spectrum into the soft X-ray regime. Specific plasma geometries that Dr. Ruden has studied (interferometrically and by other means) include gas-puff Z-pinches, capillary discharge Z-pinches, longitudinally accelerated compact toroids (spheromaks), and high pressure plasmas compressed by electromagnetically imploded solid liners. In addition, he has significant experience in solid material elastic-plastic flow physics. Experimental accomplishments in this area include the development of fast closing valves and blast shutters using implosions driven electromagnetically (θ-pinched) or by chemical explosives, and a cryogenic frozen fiber extrusion system. Dr. Ruden has also performed theoretical work in the high strain rate elastic-plastic flow of metals which has lead to improvements in the treatment of shock and plastic work heating, and the plastic and Rayleigh-Taylor instabilities of strongly accelerated solids. Representative authorships and coauthorships include:

- J.H. Degnan, et. al., "Formation, Compression, and Acceleration of Magnetized Plasmas", *Current Trends in International Fusion Research*, E. Panarella, ed., 179-196, Plenum Press, New York, NY, 1997
- F.J. Wessel, N. Rostoker, H.U. Rahman, P. Ney, E.L. Ruden, "Thermonuclear Fusion in a Staged Pinch", *Current Trends in International Fusion Research*, E. Panarella, ed., 333-345, Plenum Press, New York, NY, 1997
- E.L. Ruden and D.E. Bell, "Rayleigh-Taylor stability criteria for elastic-plastic solid plates and shells", J.Appl.Phys., July 1, 1997 issue (date tentative).
- H.U. Rahman, E.L. Ruden, K.D. Strohmaier, F.J. Wessel, and G. Yur, "Closed cycle cryogenic fiber extrusion system", Rev. Sci. Instrum. **67**, 1996, 3533-3536.
- J.H. Degnan, et.al., "Electromagnetic Implosion of Spherical Liner", Phys. Rev. Lett., **74**, 98-101 (1995).
- J.H. Degnan, et.al., "Compression of Compact Toroids in Conical-Coaxial Geometry", Fusion Technology, **27**, 107-113 (1995).
- E.L. Ruden, J.H. Degnan, T.W. Hussey, M.C. Scott, J.D. Graham, and S.K. Coffey, "Time resolved mass flow measurements for a fast gas delivery system", Rev. Sci. Instrum. **64**, 1993, 1740-1742.
- E.L. Ruden, B.W. Mullins, M.E. Dearborn, and S.K. Coffey, "Interferometry on the compact toroid formation experiments at Phillips Laboratory", Phys. Fluids B, **4**, 1800-1805, 1992.

**Dmitri D. Ryutov**
**Lawrence Livermore National Laboratory**

Dmitri Ryutov obtained his Ph.D. in Plasma Theory from the Kurchatov Institute, Moscow, Russia, in 1965. Since July 1994, he has been working as a physicist in the Energy Program at Lawrence Livermore National Laboratory. Previously he was Deputy Director at the Budker Institute of Nuclear Physics, Novosibirsk, Russia, and a junior scientist at the Kurchatov Institute, Moscow, Russia. Dmitri is generally interested in plasma physics and its applications, environmental aspects of energy production, advanced dynamics, and space plasmas. He received the I. V. Kurchatov Fellowship in 1960-62, graduated Summa Cum Laude, Moscow Institute of Physics and Technology in 1962, and is Academicain, Academy of Sciences of Russia. Dmitri also is a member of the American Physical Society, the American Association for the Advancement of Science, and the European Physical Society.

RECENT PUBLICATIONS:

[1] "Environmental Aspects of Fusion Energy", Plasma Physics and Controlled Fusion, v. 34, p.1805 (1992)

[2] "Velocity shear effects in the problem of the electron temperature gradient instability induced by conducting end walls". Physica Scripta, v.50, p.153 (1994) - in co-authorship with K.Lotov and J.Weiland.

[3] "Charge and current neutralization in the formation of ion rings in a background plasma," Physics of Plasmas, v. 1, p.3383 (1994) - in co-authorship with B.Oliver and R.Sudan.

[4] "Mirror fusion research: update and prospects," Comments on Plasma Physics and Controlled Fusion, v 16, p.375 (1995) - in co-authorship with R.F.Post.

[5] "Spinning laser targets," Comments on Plasma Physics and Controlled Fusion, v 17. p.1 (1995) - in co-authorship with D.Baldwin.

[6] "Kinetic theory analysis of sheaths and shocks," Contrib.Plasma Phys., v.36, 207 (1996).

[7] "Rayleigh-Taylor Instability in a Finely Structured Medium," Physics of Plasmas, v.3, 4336 (1996).

[8] "Submegajoule liner implosion of a closed field line configuration," Fusion Technology, v. 30. 310 (1996) - in co-authorship with P. Drake, J. Hammer, C. Hartman and J. Perkins.

[9] "Plasma convection induced by toroidal asymmetries of the divertor plates and gas puffing," Nuclear Fusion, Vol. 37, 621 (1997) - in co-authorship with R. Cohen.

[10] "The role of finite photon mass in magnetohydrodynamics of space plasmas," Plasma Physics and Controlled Fusion, v. 39 (1997).

**Kurt F. Schoenberg**
**Plasma Physics Group Leader**
**Los Alamos National Laboratory**

Dr. Kurt F. Schoenberg leads the 100-member plasma physics group (P-24) at the Los Alamos National Laboratory. Here, he directs experimental Laboratory research in Inertial Confinement Fusion, Magnetic Fusion, laser-based weapons physics, and plasma processing for industry, defense and the environment. His recent research interests and activities have focused on developing magnetically-nozzled coaxial-plasma-accelerators for advanced industrial manufacturing and advanced space propulsion. This research effort has developed a commercial manufacturing technology for microelectronics with the 3M Company.

From 1979 to 1991, Kurt was principally involved in the experimental and theoretical investigation of magnetically confined plasmas for controlled thermonuclear fusion, where he lead the ZT-40M experiment and research group. Here, his research interests included plasma dynamos, plasma sustainment by magnetic helicity injection (oscillating field current drive), RFP plasma transport by magnetic and electrostatic turbulence, similarities in edge plasma transport between tokamaks, stellarators and RFPs, and turbulence-driven anomalous ion heating. He was also a major contributor to the design and construction of the ZT-40M, ZT-P and ZTH experiments.

Over the past several years, Kurt has welcomed participation in the progressive evolution of the US Fusion program by serving on several key committees, including the New Initiatives Task Force (1992), TPX Physics Advisory Committee (1993 - 1996), TPX National Steering Committee (1995), FEAC SiCom Panel on Alternates (1996), and the FESAC ITER Panel 2 (1997). However, it is his recently acquired interest in inertial fusion, coupled with the re-awaking of the US MFE program to the need of better-cheaper-faster approaches to fusion, that motivate his present interest in pursuing MTF as a low-cost development path to fusion energy.

**Peter T. Sheehey**
**Los Alamos National Laboratory**

Peter T. Sheehey is a technical staff member in the Nuclear and Hydrodynamics Applications group (X-NH), and has been at LANL since 1991. As a computational plasma/fluid physicist, he has done multi-dimensional modeling of MTF target plasmas, such as fiber Z-pinches and MAGO, MTF-suitable high-energy liner systems, and has participated in joint U.S.-Russian MTF experiments.

**Jack Shlachter**
**Los Alamos National Laboratory**

Jack Shlachter (Deputy Group Leader, P-22 Hydrodynamic and X-ray Physics) has been at Los Alamos National Laboratory since 1979. He holds a B.S. with Honors in Physics from CalTech and a Ph.D. in Physics from University of California at San Diego. He has worked extensively in the areas of magnetic confinement fusion and high energy density physics and contributed to the development of the high-density z-pinch. His experimental responsibilities have included the design, implementation, and analysis of interferometric and x-ray data on magnetized plasmas.

Recently, he served as the project physicist for the Atlas pulsed power facility. He has authored or co-authored over a dozen refereed publications.

**Richard E. Siemon**
**Fusion Energy Program Manager**
**Los Alamos National Laboratory**

Currently, Dick Siemon is the Program Manager for LANL's $3.5-million Office of Fusion Energy research program. Los Alamos research includes ITER-relevant tritium and beryllium technology; experimental collaborations, involving plasma diagnostics on large tokamak facilities at other laboratories; theory, aimed at improved the understanding of tokamak stability limits; and an innovative concept called the Penning Fusion Experiment. Dick serves on ISCUS, the US Steering Committee for ITER. He was appointed by previous Secretaries of Energy to serve on the Magnetic Fusion Advisory Committee (1986-1990) and the Fusion Energy Advisory Committee (1990-1994). From 1978 to 1988 Dick was the Group Leader of a 30-person group that carried out extensive studies of the Field Reversed Configuration. Before that he worked on numerous non-tokamak concepts including high-beta stellarators, linear theta pinches, and multiple magnetic mirrors. A Fellow of the American Physical Society, his experimental research included advances in plasma diagnostics, such as holographic interferometry, and innovations for Thomson scattering. Prior to termination of US alternative concept research in 1990, Dick was in the Los Alamos CTR Division office as Fusion Energy Program Manager, where he helped supervise construction of the $75-million Compact Physics Research Facility, which was intended to study, as a first step, the ZT-H Reversed Field Pinch. In 1995, Sig Hecker, Laboratory Director, appointed Dick as one of six Los Alamos Industrial Fellows, a pilot program to improve Laboratory outreach to US Industry. Dick spent one year at Dow Chemical headquarters in Midland, Michigan. Following that he has served approximately half time as the laboratory-wide coordinator of the ongoing Industrial Fellows Program, and he continues to work with Dow Chemical as a consultant on management issues surrounding the use of external R&D.

**Dr. Y. C. Francis Thio**
**Massey University, Auckland, New Zealand**

A versatile experimental, theoretical and computational physicist, Dr. Francis Thio is an international with a track record in a number of high energy density physics areas including fusion energy, pulsed power, electromagnetic launch, impact physics and warheads, as well as areas in geophysics and biophysics. He has authored over 50 technical publications in these areas combined and hold four patents. He was among the first researchers to set the record of launching a gram-size projectile reproducibly in the laboratory to orbital velocity (8.2 km/s) using a high density plasma driven by submegagauss magnetic field in 1986.

He has made fundamental contributions to the analytical and numerical solution of equations of mathematical physics in the area of electromagnetic fields, geophysics and plasma physics. He has made computations of the transport properties and the equation of state of dense and strongly coupled plasmas ($10^{24}$ to $10^{28}$ $m^{-3}$, with non-ideal parameter $\gamma > 0.5$), and the simulations of plasmas using finite-difference MHD codes, with implicit methods and flux-corrected-transport (FCT) algorithm. In solid mechanics, he has performed critical mechanical design of high power electromagnetic equipment using finite-element stress analysis. In instrumentation, he has designed, developed and/or applied magnetic probes, pulsed current probes, electrical (plasma) probes, voltage probes, x-ray probes, and emission spectroscopy, including extensive experience in optoisolation, optoelectronics, digital data acquisition, computer control of experiments, high-speed pulsed electronics, computer data manipulation and analysis.

He has been a Principal Investigator and Program Manager of research programs and grants totaling more than $40 M over a period of 15 years from 1982 to 1996 in the US prior to an appointment in New Zealand. He has held assignments as Scientific Advisor and/or Consultant to Los Alamos National Laboratory, Strategic Defense Initiative Office (Pentagon), Defense Nuclear Agency, Naval Air Engineering Center (Lakehurst, NJ), David Taylor Research Center(Annapolis, MD), and SPARTA, Inc.

Employment record:

1996-Present: Section Leader, Mathematics, Massey University, Auckland, New Zealand.

1991-1996: Associate Professor of Physics, University of Miami, Coral Gables, FL.

1988-1990: Scientific Associate, Physics Division, Los Alamos National Laboratory.

1986- 1988: Senior Research Physicist, GT-Devices (subsidiary of General Dynamics), VA.

1982 - 1986: Senior Research Scientist, Westinghouse R&D Center, Pittsburgh, PA.

1978 - 1982: Research Scientist, Aeronautical and Maritime Research Laboratory, a National Laboratory of the Defence Science and Technology Organization, Australia.

1977 - 1978: Postdoctoral officer, Computer Science, Monash University, Melbourne, Australia.

**Visiting Appointments:**

1997, 1998: Consultant, Los Alamos National Laboratory.

1994-1995: Senior Fellow, Physics Division, Nanyang Technological University, Singapore.

1994, 1995: Summer Faculty, High Energy Plasmas Division, Phillips Laboratory, Kirtland AFB, NM.

1989-1990: Visiting Associate Professor, College of Engineering and Physics, U. of Illinois at Urban-Champaign, Illinois.

Distinctions/Honours:

1996-Present Associate Editor of *Physics Essays*.

1994-Present Member of the International Steering Committee, Symposium on Current Trends in International Fusion Research.

1986 Westinghouse Signature Award of Excellence for outstanding contributions in plasma science.

1982 The Australian Defense Science and Technology Organization Achievement Honour, Inaugural Award for outstanding contributions in electric propulsion.

1974-1977 The Australian Commonwealth Postgraduate Research Award.

1969-1973 British Commonwealth Colombo Plan Undergraduate Scholarship.

**Peter J. Turchi**
**Air Force Research Laboratory**

**Education:** BSE (1967), MA (1969), PhD (1970), Aerospace and Mechanical Sciences, Princeton University, Princeton, NJ.

**Career highlights:** Plasma Physicist, Air Force Weapons Laboratory (1970-72); Chief, Plasma Technology Branch, Naval Research Laboratory (1977-80); Director, Washington Research Laboratory, R&D Associates, Inc. (1981-89); Professor, Aerospace Engineering, Applied Mechanics and Aviation Department, The Ohio State University (1989- present); Senior Research Scientist, IPA, Phillips Laboratory (1990-present); Visiting Chief Scientist for Advanced Weapons and Survivability, Phillips Laboratory (1996-1997).

**Research area:** high energy density plasma and pulsed power systems, including imploding liner systems for controlled fusion at megagauss magnetic field levels.

**Related patents (P.J.Turchi):**

1. "EM Implosion X-ray Source", with W.L. Baker (1973).

2. "Stabilized Liner Implosion System", with D.J. Jenkins (1979).

**Other relevant professional activity (P.J.Turchi):**

DoE Panels on Alternative Fusion Concepts (1977 - 1978)

DoE Review Panel on Field Reversed-Mirror Plasma Generation (1978)

Editor, Megagauss Physics and Technology, Plenum Press, NY (1980).

Board of Directors, Megagauss Institute (1979 - present)

--- Chairman (1979 - 1991)

International Advisory Committee for Megagauss Conferences (1978 - present)

**M. Tuszewski**
**Los Alamos National Laboratory**

Michel Tuszewski is a plasma physicist at LANL since 1980. He became an Applied Plasma Team Leader and a Laboratory Fellow in 1997. He received an Engineering and Physics M.S. from the Ecole Centrale de Paris, France, in 1971. He came to UC Berkeley in 1972 with Fullbright and French Government grants. He received MS and PhD in Nuclear Enginnering from UCB in 1973 and 1976, respectively. He was a research associate at Cornell University (1977-1978), a lecturer at UCB (1978-1979), and a visiting scientist in France (1986) and Japan (1990).

Tuszewski combines experimental and theoretical plasma physics skills. He has studied magnetic fusion since 1973, including Multiple Mirrors, Relativistic Electron and Ion Beams, Compact Torii, and Tokamaks. He is an acknowledged expert in the area of Field Reversed Configurations. Recently, he has developed research interests in inductive discharges for materials processing and in Magnetized Target Fusion.

He has published over 100 refereed journal articles in various fields of plasma physics, including an FRC Review Article in Nuclear Fusion. He has written one book chapter, signed 4 CRADAS, and filed 5 patents in plasma processing. He is a reviewer for many scientific journals and DOE panels. He joined the American Physical Society in 1975, became an APS Fellow in 1989, and an APS life-member in 1990.

**Glen A. Wurden**
**Los Alamos National Laboratory**

Glen A. Wurden, presently a staff physicist and Team Leader of the MFE Section in the P-24 Plasma Physics Group at Los Alamos, was born on Sept. 9, 1955 in Anchorage, Alaska. He attended public schools in western Washington, and went to the University of Washington on a National Merit Scholarship. There he earned three simultaneous B. S. degrees, in Physics, Mathematics, and Chemistry, summa cum laude (1977), graduating with the highest class honors as President's Medalist. He was awarded a National Science Foundation Graduate Fellowship, and chose Princeton University's department of Astrophysical Sciences to specialize in Plasma Physics for his M.S. (1979) and Ph.D. (1982) Degrees. He is a member of Phi Beta Kappa, IEEE, and the American Physical Society.

He spent the summer of 1979 as a staff physicist working on x-ray and alpha particle imaging of inertial fusion targets on the Shiva laser at Lawrence Livermore Laboratory in California. Upon finishing his Ph.D. degree ("$CO_2$ Laser Scattering on Radio-Frequency Waves in the Advanced Concepts Torus") at Princeton, he obtained a position at Los Alamos National Laboratory in New Mexico as a J. R. Oppenheimer Postdoctoral Fellow in the CTR-8 plasma diagnostics group, and after two years, a permanent staff position in the CTR-2 reversed field pinch experimental group. In August 1988 he moved to Germany for 16-months as a DOE Exchange scientist, working in the Max Planck Institute for Plasma Physics on the ASDEX tokamak, in Garching near Munich. After his return to Los Alamos at the end of 1989, he worked on the ZTH construction project (FIR interferometer, soft x-ray arrays, pellet injection) before taking a leave of absence to the U of Washington as an Acting Associate Professor of Nulcear Engineering in August 1990. He returned to the P-1 group (High Energy Density Physics, now P-24 Plasma Physics) at LANL in April 1992, and is presently working on diagnostic collaborations at TFTR (Princeton), JT-60U (Naka, Japan), Alcator C-Mod (MIT), and HBT-EP (Columbia University). He is a member of the ATLAS Design Team, principally involved in diagnostic, target chamber, and MTF issues.

His research interests include a wide range of plasma diagnostic techniques, and their application to better understanding complex processes in hot fusion plasmas. He has particular research interests in far-infrared lasers, laser scattering, bolometry, fast pellet injection, fast x-ray and visible light imaging, neutron measurements, and concept improvement in fusion devices.

G. A. Wurden, B. J. Peterson, and Shigeru Sudo, "Design of an imaging bolometer system for the large helical device", Rev. Sci. Instru., 68(1), 766-769 (1997).

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G. A. Wurden, M. Sasao, D. Mansfield, “Alpha particle detection via Helium spectroscopy in Lithium pellet cloud”, LA-UR-94-667, Alpha Particle workshop, Princeton, NJ, March 2-4, 1994.

G. A. Wurden, S. Jardin, D. Monticello, H. Neilson, “Disruption control strategies for TPX”, LA-UR-93-2367, US-Japan Workshop on Steady-State Tokamaks, Kyushu, Jun 29-July 2, 1993.

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G. A. Wurden, P. G. Weber, R. G. Watt, et al, “Pellet refueling of the ZT-40M reversed field pinch”, Nuclear Fusion 27(5), 857-862 (1987).

G. A. Wurden, “Soft x-ray array results on the ZT-40M RFP”, Phys. Fluids, 27(3), 551-554 (1984).

G. A. Wurden, “Ion temperature measurement via laser scattering on ion Bernstein waves”, Phys Rev A, 26(4), 2297 (1982).

**Frederick J. Wysocki**
**Los Alamos National Laboratory**

Frederick J. Wysocki is an experimental physicist specializing in plasma physics. He has worked on the spheromak magnetized-plasma configuration at both the Princeton Plasma Physics Laboratory (PPPL) and at the Los Alamos National Laboratory (LANL). The work at PPPL was in the context of controlled thermonuclear fusion, while the spheromak work at LANL was in the context of the defense program and a novel approach to achieving hypervelocity. During his time at AT&T Bell Laboratories Fred built a positron trap for the purposes of producing a single-component positron plasma. Before leaving Bell, trapping of positrons was successfully demonstrated. Within P-Division at LANL, Fred has worked on several high particle and energy density plasma configurations, including the high-density-Z-pinch (HDZP) ZEBRA project, foil-implosion z-pinches and plasma-flow vacuum-opening-switch development in the Trailmaster, Athena, and HEDP programs, and the dense-plasma-focus (DPF) configuration on the Colt facility. Recently, Fred is working on developing a target plasma for magnetized target fusion using the Colt facility and funded by LANL internal LDRD funds. Fred's expertise includes diagnostics (magnetic probes, laser interferometry, Thomson scattering, Lagmuir probes), data analysis and interpretation, plasma modeling including running 2-dimensional magnetohydro-dynamic simulation codes, data acquisition, pulsed-power technology, facility operation, and the design and execution of plasma experiments.